Critical Elements for New Energy Technologies

An MIT Energy Initiative Workshop Report

April 29, 2010

Massachusetts Institute of Technology

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APS physics

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MRS Materials Research Society

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PREFACE

About the Workshop on Critical Elements for New Energy Technologies

On April 29th, 2010, the Massachusetts Institute of Technology's Energy Initiative (MITEI), together with the American Physical Society's (APS) Panel on Public Affairs (POPA) and the Materials Research Society (MRS), co-sponsored a *Workshop on Critical Elements for New Energy Technologies* that took place at MITEI's headquarters at MIT. The possibility that important new technologies for the generation, transmission, storage, or use of energy might be constrained by limitations on the availability of certain elements has only recently attracted significant attention. The purpose of the APS/MRS/MITEI workshop was to bring together experts in the diverse areas that bear on this novel issue and to try to determine the context, scope, complexity, and finally, the seriousness of the problem. The workshop also served as the kickoff for an APS/MRS study of energy-critical elements that will attempt to draw conclusions and recommend policy on this subject.

This report summarizes the presentations and discussions that took place at the workshop. The core of the report is a rapporteur's overview of the information presented by keynote speakers and the participants' comments and points of view as they emerged in extensive discussion sessions. The report identifies many of the key issues that will dominate the discussion of energy-critical elements in the future. A summary of key issues and themes, gleaned from the presentations and discussions, precedes the full rapporteur's report. In keeping with the exploratory nature of the meeting, however, the report refrains from drawing conclusions and making recommendations.

The issues at hand span an enormous range of disciplines including mining, mineral extraction and processing, mineralogy, geochemistry, economic geology, materials research, physical chemistry, condensed matter physics, and the associated engineering technologies. The political, geopolitical, and economic aspects of the problems cannot be ignored. The workshop brought together experts from all these fields to focus on whether constraints on availability pose a fundamental problem for the large-scale deployment of novel energy technologies. Participants came from diverse backgrounds and included approximately 40 representatives of academia, government, and industry. The attendees and their affiliations are given in Appendix VI. This invitation-only event was designed to open perspectives and elicit the greatest possible exchange of views, as is appropriate for a meeting that defines the beginning of the APS/MRS process.

The workshop was organized around six topical "white papers" commissioned from experts. Most white papers were circulated in advance, allowing other invitees to read and react. Several participants either asked or were chosen to prepare responses to the white papers. Two of the responses were so pertinent that we decided to reproduce them at length in this report along with the commissioned white papers. During the workshop itself, 30 minutes was devoted to a synopsis of each white paper. Each synopsis was followed by 30 minutes of discussion, including formal response(s) if appropriate. Further open discussions were held at the end of the morning and afternoon sessions. The workshop closed with a summary given by co-chair Jon Price.

The focus of the conference was on constraints on availability, whether they are real, and if so, what might be done about them. The constraints might be fundamental, geologic, technical, socioeconomic, political, or economic. Recent conferences have focused on specific elements, rare earths or lithium, for example. The APS/MRS/MITEI workshop focused, instead, on issues, introducing specific elements for illustration. The morning session was devoted to laying out the situation for three specific examples: rare earths, tellurium, and helium. In the afternoon the attention turned to crosscutting issues such as the challenges of developing a substitute for a scarce material; the way that information on mineral production and reserves is gathered by the Minerals Information Team of the US Geological Survey; and the way that other countries have responded to potential shortfalls of energy-critical elements. The workshop was conducted under the Chatham House rule to stimulate fuller discussion of critical issues. That is, with the exception of the white papers and the prepared remarks of respondents, there are no specific attributions in this report.

The workshop organizers would like to thank the workshop participants for sharing their time and insight, and for enabling us to have so productive a meeting with such a diverse group of experts. We thank the authors of the white papers and responses for allowing us to use their presentation materials in this report, and the participants who served as "scientific secretaries" during the discussion sessions. We thank the APS, MRS, and of course, MITEI and its director, Ernie Moniz, for their support. We are grateful to Ms. Jeanette Russo of the APS and Ms. Karen Gibson of MITEI without whose organizational support this workshop would have been impossible. We would like to thank Ms. Rebecca Marshall-Howarth of MITEI for editorial support of the Workshop Report.

Finally, we wish to thank Dr. Qudsia Ejaz, who served as rapporteur for this conference. Dr. Ejaz drafted the Rapporteur's Report from the white papers, the discussion summaries prepared by scientific secretaries, a recording of the meeting, and her own notes on the discussions. She also supervised the preparation and production of the published report. Without her help this report would not have been possible.

Bob Jaffe and Jon Price, Co-Chairs

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INTRODUCTION

Workshop on Critical Elements for New Energy Technologies

The potential impact of carbon dioxide (CO_2) emissions on climate and the pressure of increasing demand for energy have stimulated research into novel sources of energy and novel ways to store, transmit, and transform it. Advances in physics, chemistry, and material science have allowed researchers to identify elements with properties that can be finely tuned to their specific needs and to employ them in novel technologies. Elements like lanthanum, neodymium, tellurium, indium, or gallium, which were once laboratory curiosities, are now routinely mentioned when novel energy technologies are discussed. Many of these elements are not at present mined, refined, or traded in large quantities.

The spectrum of novel applications of rare elements is not limited to energy technologies. Ubiquitous devices like cell phones contain many elements that had few commercial applications 30 years ago. As Dr. Jung-Chan Bae suggested in his talk, we may be leaving the "Steel Age" and entering a "Rare Elements Age," when these unfamiliar substances will play an increasingly important, if surreptitious, role in our lives. Extreme variations in the price of some of these elements over the past decade hint at a complex interplay between rapidly growing demand and limited supply that may become more widespread in the near future. Although the impact of constraints on rare element supplies may reach into every area of the economy, our concern focuses on their effect on new energy technologies.

Historically researchers have paid little attention to availability when searching for materials with specific electronic or magnetic properties. Given the scope of the world's energy needs, a technology with the capacity to have a significant impact necessarily involves vast quantities of material. If a new technology that employs a rare element were to be widely deployed, widely enough to make a significant contribution to our energy needs, quantities of the rare element might be required that exceed present production, perhaps by orders of magnitude. We shall refer to such an element as (potentially) an *energy-critical element* (ECE). A cursory review suggests that some of these ECEs may not be available in the quantity and/or at the price necessary to permit large-scale deployment of what might otherwise be a game-changing technology.

The constraints on availability may take many forms. Some potential ECEs, tellurium and rhenium for example, simply are genuinely rare in the earth's crust. Rhenium, for example, is about a factor of 5 rarer than gold. Others are not so rare, but are seldom concentrated in ores. All of the so-called rare earth elements (REEs), many of which appear on lists of ECEs, are more common than silver, and a few like lanthanum, neodymium, and cerium are almost as common as copper. However REEs are not often concentrated by geochemical processes, so they rarely form economically practical ores. Furthermore the geological and mineralogical variability of REEs is relatively poorly understood, so the nature, extent, and economic value of reserves is hard to assess. Still other potential ECEs are at present obtained primarily as *co-products* or *by-products* during the refining of other primary ores, especially copper, zinc, and lead. This applies to tellurium, now obtained as a by-product of electrolytic processing of copper ore, and indium, obtained from primary zinc ores. By-products present special economic issues: it is unlikely that the mining of copper (production value ~$6.2B in 2009) would be driven by an increased demand for tellurium (production value ~$20M in 2009); although the way that copper ore is processed might well be modified to win more tellurium. Environmental issues may affect availability. Some potential ECEs are toxic; others are now obtained in ways that produce environmental damage that is unacceptable in most countries. New mining ventures require long and complex permitting processes. The existence of secondary markets is quite variable: recycling is highly developed for platinum group elements (PGEs) for example, but almost nonexistent for some other ECEs. Last, but far from least, ECEs are unevenly distributed across the world, leading to important political considerations. Even if resources exist, the extent or even absence of extraction, refining, and processing infrastructure can significantly influence international trade in ECEs. Consider, for example, the "crisis" in REEs that has attracted much media attention recently. Not only is over 95% of these critical elements produced in China, but furthermore China is rapidly becoming the center for REE extraction and processing expertise, which is hard to find in the US.

Motivated by the potential impact of constraints on availability of ECEs on emerging energy technologies, the American Physical Society's Panel on Public Affairs, and the Material Research Society, initiated a study of *"Critical Elements for New Energy Technologies"* in the fall of 2009. *"The purpose of the study is to evaluate constraints on availability of chemical elements that might obstruct the large-scale deployment of new technologies for the production, transmission, efficient use, or conservation of energy."* The key words are <u>energy</u> and <u>large-scale deployment</u>. The general subject of minerals availability is huge and inextricably connected to almost every aspect of our culture and economy. By limiting its attention to elements that have the potential for major impact on energy systems and for which high demand comes as a novelty, the APS/MRS study expects to achieve a focus and impact that a broader and necessarily more diffuse study could not.

The APS/MRS study group has teamed up with the Massachusetts Institute of Technology's Energy Initiative to convene the workshop reported here as a way of establishing the scope of this problem, identifying the central issues, and beginning a discussion of possible responses. The APS/MRS study group members were all participants in the workshop (the study group membership is listed in Appendix VII). In addition we were joined by a distinguished group of experts from academia, business, and industry, including several corporate members of MITEI. A list of all the participants and their affiliations can be found in Appendix IV.

The joint APS/MRS/MITEI workshop, *Critical Elements for New Energy Technologies*, like its parent APS/MRS study, focused on issues, not specific elements. From what we have already learned, it is clear that every element raises its own unique concerns: even the REEs must be split into the heavy and light rare earths with quite different mineralogy and geographical distribution. Any realistic discussion of ECEs must make reference to particular elements as case studies. Certainly REEs, lithium, or elements like tellurium and indium, which figure in thin-film photovoltaics, deserve careful study in their own right. Indeed, useful studies of specific elements can now be found in the literature. However, to the extent possible, it is our intention to keep the focus on the general features of the problem, not on the idiosyncratic difficulties that afflict one element or another. In this workshop, our objective has been to keep the focus on commonalities and on the nature of the issues that affect availability of rare elements and that ought to influence responses to anticipated constraints on availability. We have attempted to achieve a balance between the need to draw concrete examples from the perspective of individual elements and the desire to avoid becoming lost in debate about a particular substance.

The agenda for the workshop reflects the balance between specific elements on the one hand and common issues on the other. The morning session was devoted to reports on specific materials, whereas the afternoon was focused on responses. The materials chosen for the morning presentations were rare earths, tellurium, and helium, chosen because of the wide range of problems and situations they exemplify. REEs are not particularly rare, but are rarely concentrated in ores.

Where REEs are produced, they are mined as a primary resource. Geopolitical issues are paramount: current production is highly concentrated in one country, China. So are environmental issues: some methods applied in China produce significant adverse environmental impacts that would not be tolerated in more developed Western countries. Also, many REE deposits include significant amounts of thorium, which presents an additional radiological health hazard if it is not separated during production. The geology and mineralogy of REEs has not been explored as thoroughly as more familiar nonferrous metals like copper, zinc, or lead. Substitution opportunities for REEs in energy-critical applications like high-performance, lightweight magnets, and batteries are quite limited. Dr. Anthony Mariano provided a detailed overview of the character of REE minerals, ore deposits, and reserves. Tellurium, on the other hand, is intrinsically rare, about as rare as platinum. Tellurium provides an excellent example of the economic issues associated with by-products. Dr. David Eaglesham of First Solar Corporation, discussed tellurium resources from the perspective of a rapidly expanding company that is heavily invested in cadmium-tellurium (CdTe) based thin-film photovoltaics. CdTe is one of only a handful of thin-film photovoltaic materials which has reached commercialization, but the possibility of substituting other more common materials has recently begun to attract considerable attention. Finally, helium provides a different perspective. Helium has been stockpiled in the US since 1925 and the stockpile has been the subject of considerable debate over the past decades. Dr. James Lancaster of the National Academy of Sciences summarized the recent National Research Council (NRC) report on *Selling the Nation's Helium Reserve*. In some ways helium is a unique resource. Once the natural gas reservoirs in which helium is found have been drained, the helium is essentially gone forever — dispersed into the atmosphere. Unlike other by-product resources, it cannot be recovered from mine "tailings" at a later date. Several of its energy-related applications, like cryogenics and as a working fluid in high-temperature gas-cooled nuclear reactors, are likewise unique. On the other hand, the lessons of helium stockpiling over the past eight decades should not be ignored when calls for stockpiling of ECEs are raised in response to anticipated shortages. Each of the three morning talks was followed by a discussion, and the morning session was concluded by a further extended discussion of all three topics and related issues.

The afternoon session of the workshop focused on responses to constraints on resource availability. White papers addressed the opportunities for substitution of more plentiful materials, on the development and dissemination of information about the resources and reserves, and on the way that two other countries have formulated national policies on mineral resources.

The talk by Dr. Cyrus Wadia of Lawrence Berkeley National Laboratory and the Office of Science and Technology Policy considered the opportunity for substitution of more common elements for potentially rare ones in several applications, notably photovoltaics, batteries, and REE applications. This was followed by a review of the commodity information now provided by the Minerals Information Team of the US Geological Survey (USGS). Mr. Scott Sibley provided the USGS perspective on the dynamic way that reserves are estimated and the relation between utilization and estimated reserves. His talk provided a baseline against which proposals for enhanced information gathering and dissemination can be evaluated. In the last white paper of the afternoon, Dr. Jung-Chan Bae, of the Korean Institute for Industrial Technology, described the rare metals policy that has been developed by Korea. Although Korea's situation is different from the US — they have almost no internal sources of ECEs — the forcefulness and clarity of the Korean government's response to looming shortages might serve as a model for future US government policy.

Several extended “responses” to the afternoon white papers have also been incorporated into this report. The first, by Mr. Leonard Surges of the Natural Resources Canada, gave a perspective from a country which acts as one of the largest sources of mineral resources. The way in which Canada manages its mineral wealth, especially the interplay between public and private ownership and investment, provided an interesting model for public/private collaboration. A second, by Ms. Dayan Anderson, focused on public education and outreach on rare elements. Finally, since time did not permit us a separate white paper on secondary production and recycling, we were fortunate to have a presentation on that subject by Dr. Randy Kirchain from MIT. Each afternoon presentation was followed by an extended discussion. The morning and afternoon programs closed with animated general discussion, and the workshop concluded following a summary by study co-chair Dr. Jon Price.

SUMMARY OF KEY ISSUES AND THEMES

The APS/MRS/MITEI Workshop on Critical Elements for New Energy Technologies explored common issues and themes for elements required for emerging energy technologies geared towards reducing carbon emissions. This summary from the rapporteur's report represents issues raised, discussed, and explored by different participants of the workshop; however, they do not reflect a consensus or recommendations from the participants, nor do they represent the views of the rapporteur.

Rare Earths and Related Issues

The Nature of Economic REE and Y Minerals on a World Level, by Dr. Anthony Mariano

- Rare-earth element production is currently concentrated in China, which has several competitive advantages, including its toleration of greater environmental degradation than would be acceptable in the US.
- Current supply concerns affect all rare earths, but are most serious for heavy rare earths.
- New potential sources, such as eudialyte, are promising future options, but pose technical challenges. Research and development work is needed.
- Amenability to mining, given a favorable political and regulatory environment, is essential for production of rare earths.
- Mining projects need long lead times, commonly 10 to 15 years after exploration, confirmation of discovery and delineation of the resource. This is a function of politics and regulations, which can increase or reduce the time needed by an order of magnitude.

Cadmium/Tellurium and Related Issues

Tellurium for Photovoltaics, by Dr. David Eaglesham

- Industries with a high compound (annual) average growth rate stress the commodity supply markets in many ways. The cadmium-tellurium photovoltaic industry currently has a growth rate greater than 100%.
- It takes a long timescale for supply constraints to relax in response to demand increases, and resulting price volatility present significant challenges to corporate planning. The relaxation time for the supply constraints is determined by the time required to plan and build new plants.
- If supplies of tellurium obtained as a by-product of copper production prove insufficient, several other tellurium sources can be brought into play, though the associated time constants are hard to predict.
- Additional supplies of a rare element subject to rapidly increasing demand can be generated by substitution in other lower-value uses, although this requires re-engineering, re-tooling, and re-certification. Again, the relevant time constants are not known.
- Since the markets for rare elements like tellurium are small, they are subject to speculative manipulation. The advent of new applications or the discussion of possible shortages can trigger speculation, which has more negative impact than any real shortage of the element. There is evidence that past dramatic price fluctuations of indium and other rare elements were driven by speculation, not by actual supply constraints.

- While a counter-Malthusian (decreasing) price trend for tellurium has been observed when averaged over many years, it is not obvious that this will continue as demand increases and resource quality drops. A U-shaped curve may lie in the future.

Helium and Related Issues

Selling the Nation's Helium Reserve, by Dr. James Lancaster

- Government intervention in markets can have a host of unintended consequences.
- Helium, in some gas fields, is a by-product of a much larger commodity, which means that higher prices do not necessarily encourage supply increases.
- Reserves of helium are not stationary – i.e., if helium is not recovered at the time of production of natural gas (or liquefied natural gas), it is lost to the atmosphere.
- There is limited information available on supply of and demand for helium. The market is a small niche market, which increases opaqueness. An effort should be made to improve data collection and information availability.
- Helium has special physical, chemical, and nuclear properties which make it indispensable for many applications.
- A small but important segment of helium consumers are researchers in small academic institutions and national labs. They have limited flexibility to respond to price increases, and are disproportionately affected by them. Efforts should be made to protect small but key consumers in research from the negative impacts of helium price increases.

Substitutional Research in Physics, Chemistry, and Materials Science

Mined Resource Constraints on Solar Energy and Battery Storage Potential, by Dr. Cyrus Wadia

- Elements and materials required for energy technologies have applications in other technologies, such as computers, which compete for supplies.
- Energy technologies can be materials intensive — a "materials hog."
- Other potential semiconductors for photovoltaic applications exist with favorable extraction economies and theoretical efficiencies. They need more research and development to overcome practical challenges.
- Development of these potential new technologies, however, should not occur at the expense of use and development of existing technologies.
- While there are sufficient reserves in the ground to meet projected needs, large-scale deployment would require increases in annual production for most photovoltaic and battery technologies.
- There are concerns about monopoly and access restriction by China, because of their dominance in production of several key elements needed for new energy technologies.

Tracking Critical Elements in the US

Supply and Demand for Selected Energy Related Mineral Commodities, by Mr. Scott Sibley

- There is a need for transparent and accurate data of production, reserves, and reserve base for energy-critical elements.
- Higher prices increase reserves; however, reserves and production for some key elements, such as rare earths, are concentrated geographically.
- Long lead times of 5 to 15 years for new mining ventures can cause shortages and price spikes in the short term.
- China has emerged as a primary producer of energy-critical elements because of significant resources, less stringent environmental regulations, and lower labor costs.
- Scrap and recycling could present significant sources of supply in the short term if secondary markets are developed. Substitution in other lower-value applications occurs over longer timescales.
- The definition of "reserves" and "reserve base" is imprecise and nonuniversal, making estimates of available resources difficult to quantify.
- The US Geological Survey is constrained by resources and cannot conduct a comprehensive estimate of reserve base for energy-critical elements.

Materials Policies of Other Nations

Strategies and Perspectives for Securing Rare Metals in Korea, by Dr. Jung-Chan Bae

- Ensuring supply of rare metals, especially strategic critical elements, is a priority for the Korean government.
- Materialization, i.e., the establishment of industry to produce finished materials for use in consumer products, is an important component of Korea's strategy.
- Recycling has the potential to emerge as a significant alternative resource.
- An efficient and comprehensive system is needed to realize the full potential of recycling as an alternative resource.
- A robust structure is needed for research and development support by the government and the development of suitable industries and enterprises. This role is played by the Korea Rare Metals Center.

Supplementary Presentations

A Communications and Outreach Perspective, by Ms. Dayan Anderson

- There is limited public awareness of its mineral footprint, analogous to the earliest stages of the environmental movement.
- If efforts to conserve rare materials are to succeed, it is imperative that public awareness be raised.
- As yet, no individual or group has framed a compelling case for husbandry of rare-element resources similar to the way that Aldo Leopold and other early conservationists' work energized the environmental movement in its early days.

Considering Resource Availability for Energy Technologies, by Dr. Randy Kirchain

- Market forces can resolve most scarcity issues.
- Transient events, however, such as scarcity, can cause lasting changes in trajectory of materials technology development.
- Recycling has many potential benefits, among which are 1) ameliorating resource depletion; 2) reducing energy consumption in material production; 3) stabilization of markets; and 4) diversification of risk since primary and secondary sources are rarely identical.
- There are serious socioeconomic as well as technical barriers to increasing recycling.

Advantage Canada: Materials-Related Policies, by Mr. Leonard Surges

- Canada is an important supplier of minerals, and has significant influence and presence around the world.
- Canada's model for mineral development provides a useful contrast to the US model. In particular, mineral rights in Canada are owned by the Crown.
- The government's role is to gather and make available relevant information, provide relevant infrastructure for resource development, and provide an environment conducive to investments.

The APS/MRS/MITEI Workshop on Critical Elements for New Energy Technologies

FROM THE RAPPORTEUR'S REPORT ON THE WORKSHOP

The proceedings of the APS/MRS/MITEI Workshop on Critical Elements for New Energy Technologies are summarized in this report, which reflects the major points of discussion of the invited speakers and participants at the event. It is important to note that this is a report on the proceedings, including its papers and presentations; it is not a study. The report represents a range of views from those at the workshop; *it is in no way intended to represent the views of all the participants, of individual participants, or of the rapporteur*.

CHAPTER 1 – Morning Program: Case Studies of Materials

1.1 Rare Earths and Related Issues

Rare earth elements (REEs) have special physical and chemical properties that make them fundamental and indispensable components of modern technology, including renewable energy alternatives. The focus of this session was the mineralization of REE-rich deposits, and the criteria essential for their mining and extraction. The keynote speaker for this session, Dr. Anthony Mariano[1], gave a comprehensive presentation titled "The Nature of Economic REE and Y Minerals on a World Level[2]," that covered not only the locations of major producing and potential sites for REEs, but also discussed mineralization properties, mining processes, and the significant challenges in extraction and fabrication of REEs.

Epitome

Dr. Mariano began with some basics: REEs are a group of 16 elements[3], which are further divided into light rare earth elements (LREEs) and heavy rare earth elements (HREEs)[4]. Figure 1.1 shows the location of different deposits containing REEs, only a few of which are currently producing. They are mined as primary products or as co-products or as by-products with other metals, such as iron (Fe), platinum (Pt), and tin (Sn). The challenges in the extraction of REEs arise primarily because they occur as low-concentration, substitutional impurities in deposits, and they are difficult to isolate and separate. They are more difficult to win than gold (Au), which occurs with lower crustal abundance and lower concentration in deposits than REEs.

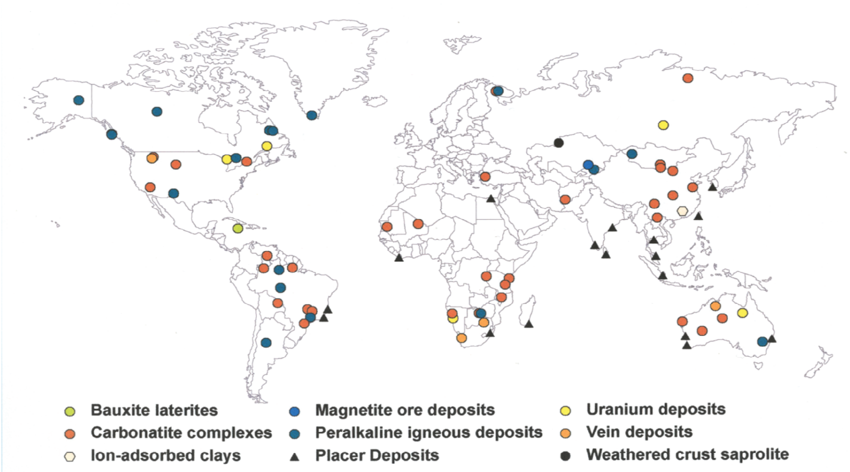
[1]Dr. Anthony Mariano, Consultant, Carlisle, Massachusetts

[2]Please see Appendices I.A and I.B for presentation and white paper.

[3]The 16 REEs are yttrium (Y), and the lanthanides. The lanthanides are a group of 15 elements: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). Some people include scandium (Sc) in REEs as well.

[4]The LREEs are the lanthanides from La up to Gd. The HREEs are Y and the lanthanides from Tb to Lu. This division is not universal. It has been chosen by Dr. Mariano based on crystal structure when they are synthesized as phosphates: the LREEs in this division form monoclinic structures (monazite), while the HREEs form tetragonal structures (xenotime) similar to the mineral zircon which contains zirconium (Zr). This occurs because of "lanthanide shortening," where the atomic radii gradually decrease with increasing atomic numbers.

Figure 1.1: The location of various REE-bearing deposits in the world is shown in this figure. The carbonatite complexes and ion-adsorbed clays in China provide 97% of current global production.



Dr. Mariano enumerated criteria for an REE deposit to be economic. These criteria are: favorable mineralogy and lanthanide distribution; grade and tonnage of the deposit; economically viable mining and mineral processing, along with successful chemical separation of individual REEs; acceptable levels of deleterious impurities, such as thorium (Th) and uranium (U); and minimum negative impact on the environment. In addition to these requirements, favorable political climate and logistical support, including access to electricity and transportation infrastructure, are prerequisites for any successful mining venture. It should also be noted that the interpretation of these requirements changes from country to country and region to region. He further elaborated on the need for a favorable lanthanide distribution and said that the use and demand for REEs in technology is in flux. Thus it is important not to narrow the focus of a production venture on just one particular REE, such as Dy. The complexity of these requirements lead to a time scale of 10 to 15 years to bring a mine to production, after exploration and confirmation of discovery.

The important sources for REEs have been some carbonatites[5] and some placers (beach and river sands). The carbonatites that have been mined for REEs contain the LREE-bearing mineral bastnaesite[6]. Mountain Pass (CA), Bayan Obo (Inner Mongolia, China), Mianning County (Sichuan, China), and Weishan Lake (Shandong, China) are REE-rich carbonatite complexes. Placers[7] contain monazite[8], xenotime[9] and other REE-bearing minerals, which, where they occur in sufficient concentrations, are produced as by-products of mining for titanium (Ti), Sn, zirconium (Zr), and gold (Au). Other sources are loparite[10] and uraninite[11].

A new source for REEs, which is HREE-rich, are the unusual, ion-adsorbed clays found in South China. These are apparently formed by hydrothermal alteration of granite followed by lateritic weathering. The HREE ions are adsorbed onto residual clays. A primary challenge in production is the low concentration (0.03% to 0.2% by weight) of rare earth oxides (REOs) compared to

[5]Carbonatite complexes are unusual mantel-derived igneous rocks that are composed primarily of carbonate minerals and bring to the surface high-field strength and exotic elements. Thus they serve as a source for REEs and niobium (Nb) and tantalum (Ta).

[6]Bastnaesite's chemical composition is $(REE)CO_3F$. The REEs are usually La, Ce, Pr, and Nd.

[7]For example, placer mining for Ti minerals ilmenite and rutile produces monazite as a by-product. Placers or beach sands are now a minor source of REEs.

[8]Monazite's chemical composition is $(REE)PO_4$; its crystal structure is monoclinic. The REEs are usually La, Ce, Pr, and Nd. Th is also present.

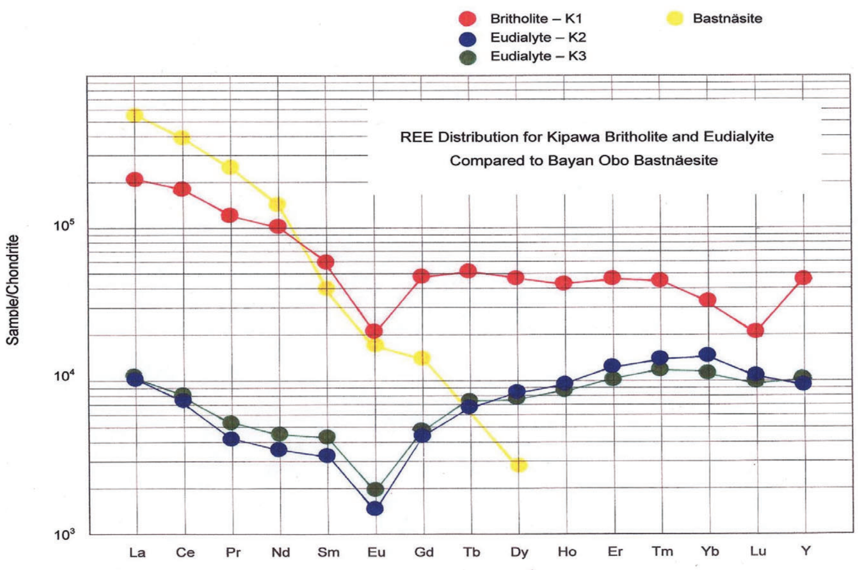
[9]Xenotime's chemical composition is $(Y, REE)PO_4$, similar to monazite, but its crystal structure is tetragonal, and the HREEs are more abundant than in monazite. It is also found in hydrothermal vein deposits. At present, there is no sustainable source of xenotime.

[10]Loparite is a mineral found in certain alkaline igneous rocks. Its chemical composition is $(REE, Na, Ca)(Ti, Nb, Ta)O_3$.

[11]Uraninite's ideal chemical composition is UO_2. It commonly contains REEs substituting for U and daughter products of the decay of U.

bastnaesite (75% by weight) or monazite. This low concentration means that large quantities of the clays have to be moved through the production process with large amounts of waste and significant environmental impact[12]. China currently is the only producer of HREEs. The South China clay deposits are economic because of low labor costs and less stringent environmental controls than in most other mineral-rich countries. Today China accounts for 97% of global REE mine production.

Figure 1.2: The concentration of individual REEs in eudialyte, britholite, and bastnasite is shown in this figure. The REE are listed along the horizontal axis in increasing atomic numbers. The LREEs are from La to Gd, while the HREEs are from Tb to Y. Their concentration in the various samples is normalized to chondrites, which are silica-rich meteorites. This concentration is shown on a log-scale along the vertical axis. The HREE rich composition of the eudialyte sample from Kipawa can be seen clearly compared to bastnaesite sample from Bayan Obo. The britholite sample, also from Kipawa, has a higher concentration of LREEs than HREEs.



Dr. Mariano also discussed the potential and challenges for deposits in which supergene enrichment (enhanced concentration through weathering) had occurred. Such a potential new site for REE production is the Mt. Weld HREE deposit in Western Australia, which was discovered in 1980. This is planned for production in the near future. At Mt. Weld, supergene enrichment of a carbonatite produced fine-grained crystals, which make the mineral processing phase of production challenging.

Dr. Mariano pointed out that other deposit types, such as ones that contain eudialyte[13] and britholite[14], may be REE resources for the future. However economic extraction technologies are needed for many of these to become profitable. He highlighted a promising potential new source for HREEs as the mineral eudialyte. The HREE-rich composition of eudialyte compared to carbonatites can be seen in Figure 1.2. There are several eudialyte-rich deposits in North America, such as Pajarito Mountain, New Mexico; Dora Bay, Alaska; Red Wine Complex, Labrador; and Kipawa, Quebec. This mineral is especially interesting because it easily dissolves in a solution of weak acids. However, a chemical process has to be found to isolate the REOs from the colloidal silica gel produced in the solution.

Discussion

There was a general discussion leading to agreement that, while the newspapers carry stories of hundreds of potential mining ventures, less than a tenth of them meet the criteria laid out by Dr. Mariano. Most of the companies in the market seek short-term revenue. Many companies fear that the size of the REE market cannot justify the investment required to open new mines or to increase production.

[12]The details can be found in the slides in Appendix I.B and the white paper in Appendix 1.A.

[13]Eudialyte's chemical composition is approximately $Na_4(Ca,Fe,Mn,REE)_2ZrSi_6O_{17}(OH,Cl)_2$.

[14]Britholite's chemical formula is $(Ce,Y,Ca)_5(SiO_4,PO_4)_3(OH,F)$.

There was also a general discussion about the time needed to bring a new mine into production or to reopen an existing facility that had been closed down. These issues depend on the regulatory and political environment at the location of the mine. The development of identical deposits may take ten times longer in one region compared to another.

One participant brought up the issue of lack of communication between miners and the ultimate consumers of the mined commodities. This has inhibited coupling between supply and demand, leading to shortages and price volatility. This effect has been especially severe where REEs are co-produced with other major commodities, such as Fe and Nb.

Another participant asked Dr. Mariano about the potential for extracting REEs from geothermal streams, and if geothermal power generators could use such an extraction for additional revenue, while mitigating environmental impacts. He replied that while he had not studied the issue in this particular context, a similar and potentially more compelling case was the HREE-enriched waste stream from the production of uranium from uraninite. In this process, uraninite is treated with sulfuric acid, which also extracts HREEs. However, when he asked Cameco, the largest North American producer of uranium which operates the Athabasca deposits in Saskatchewan, Canada, about processing further to recover the HREEs as alternative revenue stream, they said that it was not a worthwhile effort from their perspective. Regarding the question of whether REEs could be extracted from geothermal fluids, concentration in the fluids would be the key to economic recovery. It is unlikely that geothermal fluids would contain sufficient REEs to justify recovery.

It was pointed out that the present size of the global REE mining market is about $1B per year. It can be expected to grow with time, since REEs are important components in energy systems that are being widely deployed. The future value would be even larger. For example, half a ton of Nd is used in a 1.5 MW wind turbine.

The so-called REE crisis was summarized by one participant who noted that there was a confluence of several factors that hint towards a shortage in the future. These are the concentration of REE production in China and Chinese policies of restricting exports and increasing taxes on exports. On the other hand, he said that while there might be a shortage in the short term, there may be an oversupply of REEs by 2020, as high prices will bring new production online in other parts of the world.

One participant commented on potential future resources of REE. He observed that REE in phosphates of marine, sedimentary origin are low, but that as marine phosphate supplies are limited in magnitude, phosphates from igneous rocks are starting to come onstream. These igneous phosphate minerals tend to be enriched in REE. Dr. Mariano responded that while he had previously worked in this area, he did not consider it a promising avenue because of low REE concentration in igneous rocks compared to today's REE ores.

The point of Chinese competitive advantage was further explored by one participant by noting that Bayan Obo is primarily an iron mine. However, most of the iron mining at Bayan Obo is not in the same zones within the carbonatite deposit as the REE zones. REE production at Bayan Obo is properly regarded as a by-product. Consequently, China can easily undercut prices for REE and affect the profitability of other REE mines.

One participant raised the issue of the downstream value of REE and asked whether there exists the capacity and intellectual property to produce REEs from various deposits as they are brought online. In response another participant listed several applications of REEs, such as the use of Lu-based detectors at ports, instead of helium-3 (He-3)–based detectors, and the use of La for phosphate scavenging in the bloodstream of dialysis patients. If an abundant and cheap supply of La were available, it could potentially be used to clean up the whole Midwest water system.

Summary of Key Issues and Themes

- REE production is currently concentrated in China, which has several competitive advantages.
- Current supply concerns affect all REEs, but are most serious for HREEs.
- New potential sources, such as eudialyte, are promising future options, and must be further developed.
- Amenability to mining, given a favorable political and regulatory environment, is essential for production of REEs.
- Mining projects need long lead times, commonly 10 to 15 years. This is a function of politics and regulations, which can increase or reduce the time needed by an order of magnitude.

1.2 Cadmium/Tellurium and Related Issues

A key technology area for renewable energy is thin-film photovoltaics (TFPVs), which convert sunlight directly to electricity using semiconductor layers only a few microns in thickness. The high cost of silicon (Si), which must be used in much greater thickness (typically hundreds of microns) in conventional polycrystalline solar cells, drives interest in TFPVs, already an indication of the way that commodity supply can influence technology. TFPVs, depending on the technology, use small but significant quantities of unfamiliar elements such as tellurium (Te), indium (In), gallium (Ga), germanium (Ge), and selenium (Se), *which currently do not have large, mature markets*. Instead they are secondary products (by-products) from mining of important nonferrous metals, primarily copper (Cu), lead (Pb), and zinc (Zn). One of the key issues faced by TFPV producers is to secure a sufficient supply of these materials at a reasonable cost, given the traditionally small demand for them and the rapid growth of the TFPV industry.

The keynote speaker for this session on "Cadmium/Tellurium and Related Issues" was Dr. David Eaglesham[15]. In his talk titled, "Tellurium for Photovoltaics," he presented the perspective of First Solar, the largest and fastest-growing company in TFPV production today in the US and a consumer of Te, on supply-and-demand issues.

As Dr. Eaglesham's title indicates, almost all of this session focused on Te. Cadmium (Cd), on the other hand, is a by-product of Zn. Though relatively uncommon, Cd is in ample supply because being toxic, it must be removed from Zn during refining, and its use is restricted on account of its toxicity.

Epitome

Dr. Eaglesham began by noting the need for renewable energy to meet carbon reduction targets. He stated that the Intergovernmental Panel on Climate Change (IPCC) calls for 5 TW for renewable energy by 2020, which indicates a large potential for growth, although these sources have to be competitive with traditional sources of power.

He pointed out that the TFPV production costs for First Solar had been consistently dropping, from $1.59/W in 2005 to $0.84/W at the end of 2009. These cost reductions had been achieved primarily through commissioning new factories in each successive year, i.e., by economies of scale. And, Dr. Eaglesham asserted, CdTe photovoltaics (PVs) are on track to achieving grid parity with their current estimated cost of electricity production at $0.15/kWh.

Dr. Eaglesham explained that emerging PV technologies can be grouped together into two categories: TFPVs and concentrating photovoltaics (CPVs). TFPVs have a more favorable cost structure than CPVs, which has allowed them to take a larger share of the market. TFPVs come in (at least) two types: CdTe and CIGS ($CuInGaSe_2$). These use the rare elements Te, In, and Ga. The CPV design is used for the InGaAs/Ge PV, which has been pushed towards a concentrating technology because the PV substrate, Ge, is very expensive. However, if their substrate expense were lower, they would have a competitive, highly desirable, 35% efficient triple junction PV. This shows that costs determine the technology choices made in the PV industry.

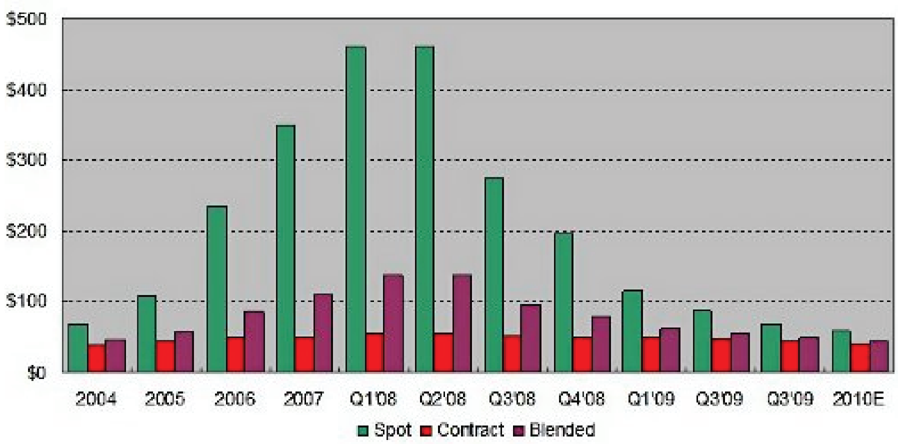
Dr. Eaglesham went on to say that CdTe TFPV is the fastest-growing PV technology with a compound average (annual) growth rate (CAGR) greater than 100%. Any CAGR greater than 30% produces tremendous stresses on the supply chain. Glass, needed in CdTe PV manufacture,

[15]Dr. David Eaglesham, Chief Technology Officer, First Solar, Inc., the largest and fastest growing company in TFPV production today in the US

provides an example. The glass industry has a CAGR of only 2%; hence trying to meet the demands of an industry with a high CAGR produced stress in the glass market.

In addition to these stresses, there are other uncertainties that affect the manufacture of PVs. For example, a transient shortage in Si wafers in 2007 to 2008 led to a Si spot market price that hit \$450/kg compared to a baseline of \$55/kg. During this same period the contract price of these wafers remained unchanged because the cost of production did not change (see Figure 1.3). This negatively affected the growth rate of the Si-based PV industry.

Figure 1.3: A comparison of spot vs. contract prices for Si wafers is shown here. The price spike from \$55/kg to \$450/kg in 2007-08 was caused by transient supply shortages, and not an increase in material or production costs.[16]



After describing supply chain stresses and outlining supply/demand dynamics, Dr. Eaglesham discussed his perspective on constraints on supply of Te. It is a by-product of Cu, for which the market is much larger and more mature. Te can be extracted during the electrolytic purification of Cu ores, where it is left behind in anode slimes. At present, not all Cu is refined in this way, and not all recoverable Te is extracted from these slimes. Some argue for a "hard limit" on the availability of Te, noting that the production of Cu is not going to be affected by the demand for Te even if the price of Te increases dramatically. Once Te production from anode slimes is exhausted, so the argument goes, a significant price spike will occur before other sources of Te are exploited. The result would be a "hard limit" on Te supply.

Dr. Eaglesham countered this argument by outlining a series of mechanisms that would function to smooth out the discontinuity. These mechanisms introduce supply/demand price elasticity. In general, he said, not all Cu ores are the same, and extraction efficiency of Te from anode slimes varies from one refinery to another. More specifically, three potential mechanisms act to increase supplies as prices increase: first, the extraction efficiency will increase in existing operations at Cu refineries, where currently ~50% of the Te is left unrecovered; second, other primary sources known to contain Te, specifically nickel (Ni) and Pb, will be processed for their Te content; and third, marginal ores will become economic because of the secondary Te production revenue. He said that he considered \$100/kg to be a healthy price level, coupled with high visibility of the PV industry, to stimulate new Te production from other primary sources. Dr. Eaglesham also stressed that, although he can make general statements about where First Solar anticipates future new Te sources, he cannot divulge specific details.

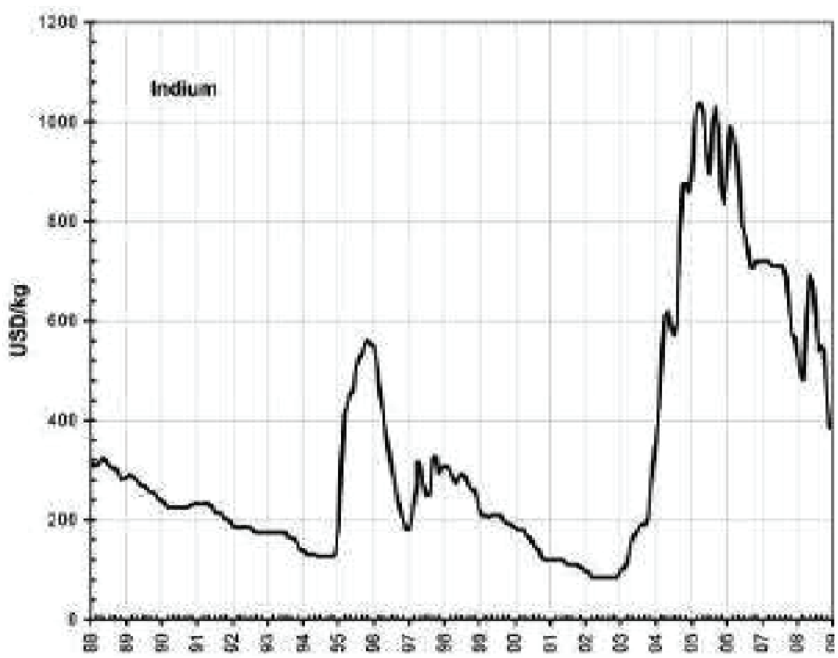
In addition, there is elasticity on the demand side, Dr. Eaglesham continued, because the thickness of the CdTe film can be reduced with a small efficiency penalty and, importantly, other Te consumers can switch to substitutes. The efficiency of CdTe depends on its thickness. This thickness can be halved with only a "1% efficiency penalty." (During the discussion it was clarified that this meant a reduction from ~11% efficiency to ~10%, in fact a reduction of nearly 10%.)

[16]Chart is available at http://www.eetindia.co.in/ART_8800597518_1800008_NT_733a821b_2.HTM

At the same time, CdTe PV production has a high resilience in the face of price increases because the cost of Te is a small component of the total solar panel cost. Even at a Te price of $200/kg, the cost of Te for current thickness CdTe PVs is less than $0.02/W, compared to a production cost of $0.84/W. Substitution in more conventional applications also provides significant demand elasticity. CdTe PVs currently consume 20% of produced Te; the rest is used to increase the machinability of steel and other metals. A natural substitute for Te in this application is Se, which is found and produced alongside Te. If this substitution were made, the Te available for CdTe PVs would increase several-fold. However, the price point needed to achieve this substitution is unknown.

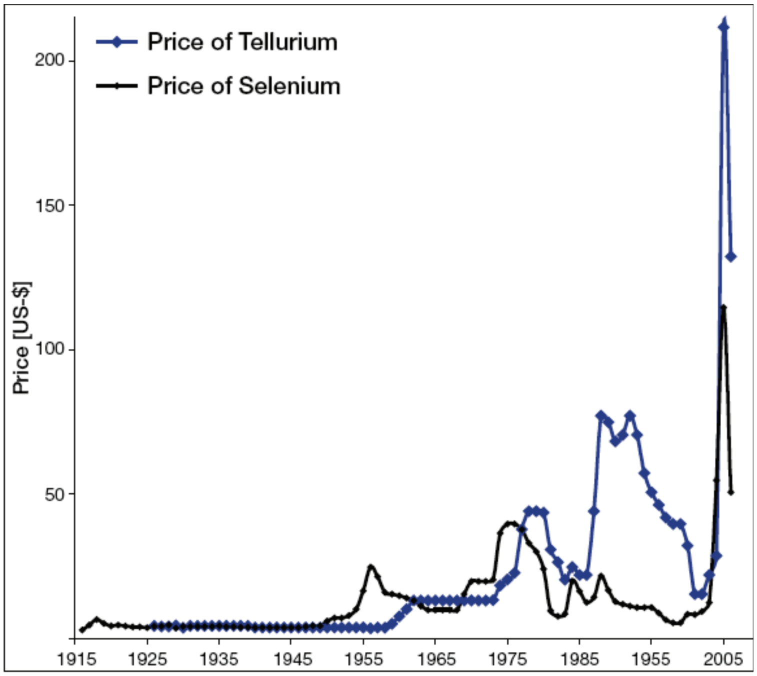
After discussing these important elasticity mechanisms, Dr. Eaglesham focused on what he considered to be two important issues that may constrain economically available quantities of Te, namely the long relaxation time of supply constraints and price volatility. He used the history of In price fluctuations to illustrate his points. Dr. Eaglesham asserted that the In data, shown in Figure 1.4, shows that major demand excursions can generate a price spike that only decays over roughly six years. Prices of In spiked in 1996 (demand for laptop screens) and 2005 (demand for flat-screen TVs); however, the cost of mining and producing In did not increase significantly during that time period. Indeed the baseline cost of In, like other raw materials, has continued to drop over the long run, indicating a counter-Malthusian trend. Indium consumers responded to these supply constraints in the short term by recycling and using thinner layers of In; however, the observed six-year time constant was driven by the time required to plan and build a new plant. So, Dr. Eaglesham went on, the difference between production cost and the high price (measured by the area under the excursion of the price curve from the long-term trend) went to speculators. While supply constraints are potentially resolvable, Dr. Eaglesham asserted that the concerns regarding price volatility have no simple, acceptable solution. Te has recently seen severe price variations, as much as two orders of magnitude above the baseline (Figure 1.5). These variations were driven by speculation, which arise from rumors and projections: the price spike in 2005 coincided with First Solar coming online and not with any increase in demand. Dr. Eaglesham emphasized that while First Solar's economic interest is best served by securing Te at the lowest possible price, he believed that new supply development would best be encouraged at a price greater than $100/kg. He noted the need for a strong national policy that aims to reduce speculative excursions and increase long-term supply while minimizing price. He also expressed a concern that meetings such as this workshop help to fuel speculation.

Figure 1.4: The price spikes caused by major demand increases for In in 1996 (demand for laptop screens) and 2005 (demand for flat screen TVs) are shown in this figure[17]. These price peaks decay over a six-year period.



[17]Figure is taken from: Peter Rigby, "The paradigm shift – implications for key materials in thin-film PV" (presented at the 2nd EPIA International Thin-Film Conference, Munich, Germany, November 12, 2009).

Figure 1.5: The price volatility shown in this figure[18] (with price measured in US dollars per kilogram) is driven by speculation, which arises from rumors and projections. The price spike in 2005 coincides with First Solar coming online vs. a substantial increase in demand. Te prices spikes can be 100 times the baseline.



Finally, Dr. Eaglesham summarized specific concerns about the vulnerability of CdTe PV deployment to potential Te shortages. He reiterated that Te is a small component of the total cost and that pricing Te out of metallurgical applications could triple quantities available to PV applications. While current Cu mining levels and refining practices can support Te production at several times current levels, long-term visibility for CdTe PV would be required to drive this transformation, lest the Cu mining and refining industry conclude that CdTe PV will soon disappear, in which case their capital investments for co-producing Te would be wasted.

Dr. Eaglesham concluded his talk on an optimistic note. He said that the potential supply of Te would support TFPV deployment in the range from 40 GW/yr to many TW/yr. And even the low estimate of 40 GW/yr grows to 1 TW of installed capacity in 20 years.

Discussion

Discussion immediately after the talk centered on clarifying some of the data on Te use in present-day TFPVs. The group generally agreed that at current efficiency and film thickness, each watt of installed TFPV capacity requires ~1/10 gm Te.[19] This means that the amount of Te needed for a TW-scale deployment is huge — approximately 100,000 metric tons per TW. It was also clarified that reducing the Te used by a factor of two would reduce efficiency from ~11% to ~10%.

One participant shared that mining companies do not report Te production because it has a reputation as a "bad metal," which causes problems winning more valuable metals. As a result, there is a lot of Te in Sn and Pb ores that does not show up in records.

Another participant commented that competition for materials is an important consideration. For example, Te is an important component in nanostructured thermoelectrics. However, the quantity required is large and is a significant portion of their cost. Consequently the demand for Te in PVs has made Te-based thermoelectrics impractical.

[18]Figure is taken from: F. Ojebuoboh, "Selenium and tellurium from copper refinery slimes and their changing applications," ERZMETALL 61, no. 1 (2008).

[19]It should be noted that "installed capacity" in the PV world is computed assuming incoming insolation of ~1 kilowatt per square meter. Even highly favorable locations average out over diurnal and seasonal variations to something closer to 250 watts per square meter. Hence the Te intensity is closer to 0.4 gm per watt of *delivered* electrical power, and 1 TW of produced electricity would require 400,000 metric tons of Te.

An industry participant countered Dr. Eaglesham's comment that Te could be priced out of metallurgical usage, noting that Te is a small component of their cost as well. Also retooling and requalification are difficult, and represent a significant hurdle to substitution in this application. Therefore, price increases alone may not free up the Te now consumed in metallurgical use for PV applications.

A question was asked about the importance of storage in large-scale deployment of PVs. Dr. Eaglesham replied that the intermittency of wind and solar energy are somewhat complementary, mitigating storage considerations. Also, plug-in hybrid vehicles could be a significant storage resource in the future.

Another participant questioned whether Te resource limitation was a consideration when First Solar was started. Dr. Eaglesham replied that the more important consideration for them had been to examine affordable supply of Te. They were not worried about a limitation in the resource. A follow-up question asked when Te availability had become an issue. Dr. Eaglesham replied that it has never been an issue since it is a tiny piece of the panel cost.

Dr. Eaglesham's use of the Erlich-Simon anecdote was challenged and it was suggested that perhaps rare materials like Te lie on a U-shaped price-versus-time curve, rather than an "anti-Malthusian" (i.e., decreasing) trajectory. The U-shaped curve would arise because prices could increase dramatically when resource quality dropped. In his response, Dr. Eaglesham asserted that people would always find a way around such issues and in the event of a true shortage of Te, a technology based on another material would displace CdTe. He stressed that substitution is fundamentally an economic issue.

Following up on the issue of speculation raised by Dr. Eaglesham, it was noted that speculation is usually driven by a futures market. Pointing out that no futures market exists for Te, what mechanism, it was asked, drove the speculative spike in price? Dr. Eaglesham replied that suppliers drove the speculation through futures contracts and through speculation in mining rights.

Finally, Dr. Eaglesham was asked if governments have a responsibility to limit speculation. He responded that it was difficult to prevent people entering into future contracts in a free market. He did not see a place for government intervention and preferred free markets.

Summary of Key Issues and Themes

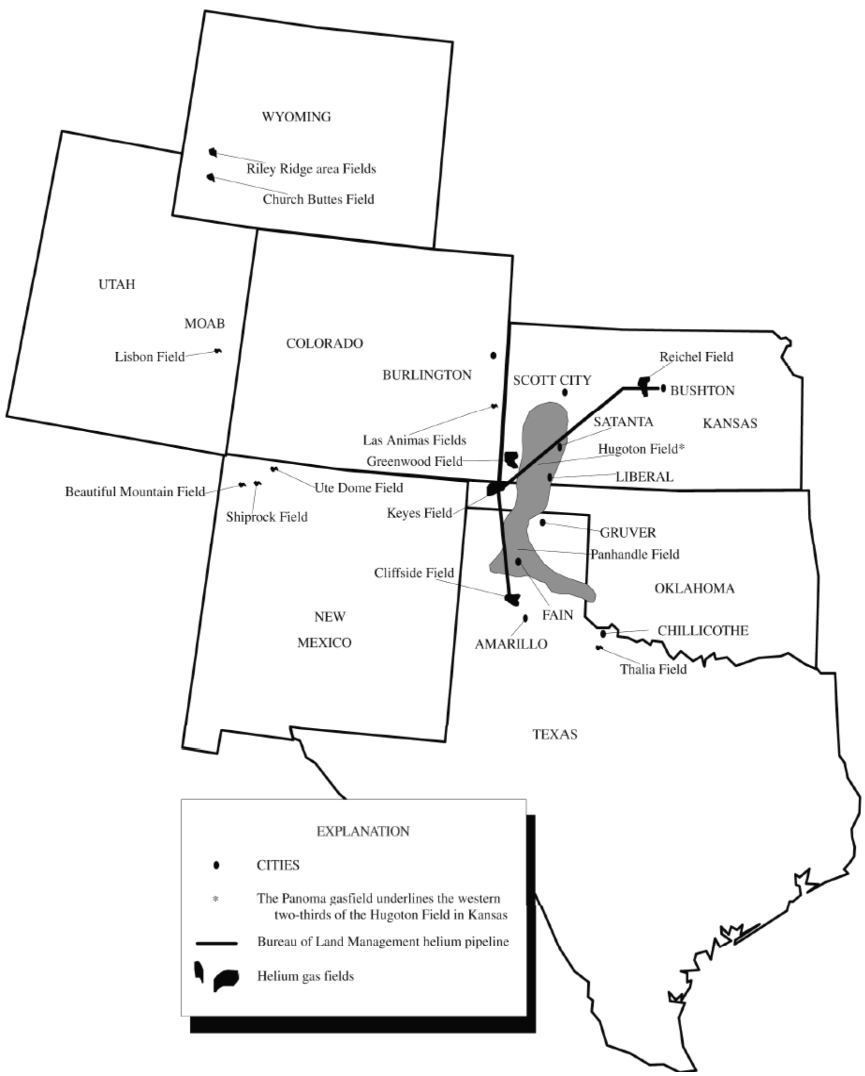
- Industries with high CAGR stress the system in many ways. The CdTe PV industry currently has a CAGR greater than 100%.
- A long timescale for relaxation in supply constraints in response to demand increases, and price volatility present significant challenges. The relaxation time for the supply constraints is determined by the time required to plan and build new plants.
- If Te supplies as a by-product of Cu production prove insufficient, several other Te sources can be brought into play, though the associated time constants are hard to predict.
- Additional supplies of a rare element subject to rapidly increasing demand can be generated by substitution in other, lower value uses. Again the relevant time constants are not known.
- While a counter-Malthusian price trend for Te has been observed over many years, it is not obvious that this will continue as demand increases and resource quality drops. A U-shaped curve may lie in the future.

1.3 Helium and Related Issues

Helium-4 (He) has several special physical and chemical properties that make it an indispensable commodity in various applications, including future potential uses in low-carbon energy technologies. It is also a co-product with natural gas. These themes make it an important example of the common issues that this conference intended to highlight. In addition, He has a history of stockpiling and regulation by the Federal government, which makes it a pertinent example when considering policy measures to stabilize supply.

James Lancaster[20], the keynote speaker for this section, gave a presentation on "Selling the Nation's Helium Reserve[21]," in which he described the NRC report that examined the effects of selling the nation's He reserve.

Figure 1.6: Federal Helium Reserve in the panhandle area, and new sources in Riley Ridge.



Epitome

Dr. Lancaster began by noting that the Federal government created the He reserve in the mid-1960s during the cold war. The government encouraged private industry to produce and sell He to it. This program was remarkably successful, as a decade later the reserve contained 35 billion cubic feet[22] (Bcf) of He, which was nearly 60 times the annual domestic consumption in 1970. The reserve was established in a reservoir in West Texas, along with a 400-mile pipeline across Texas, Kansas, and Oklahoma that connects He sources to refining facilities (shown in Figure 1.6).

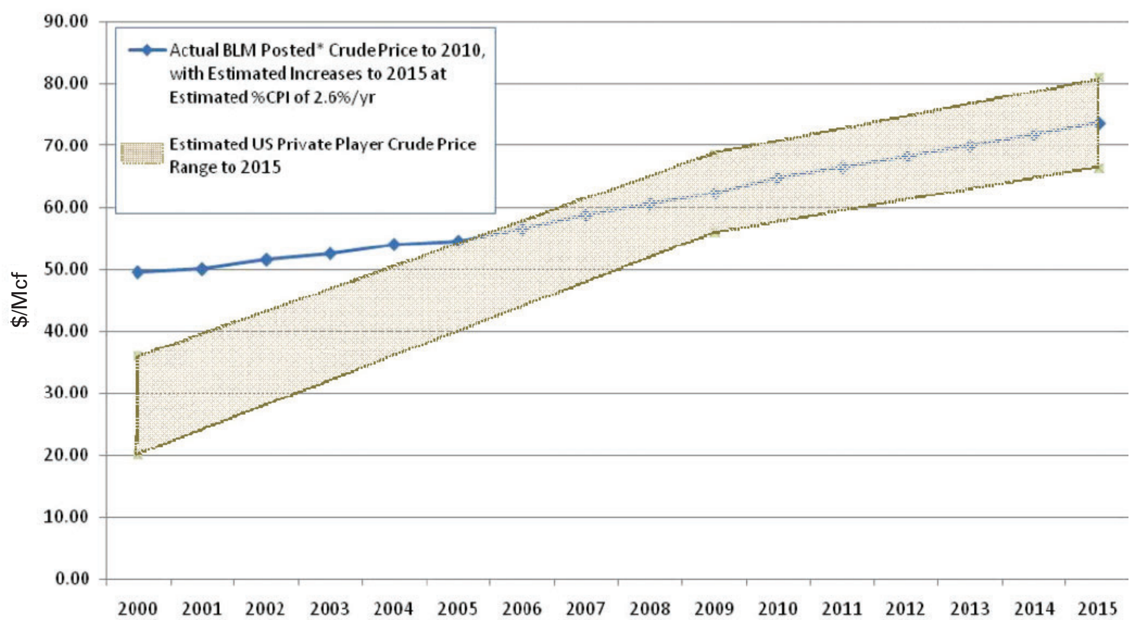
[20]James Lancaster, Program Officer, Board on Physics and Astronomy, National Research Council, The National Academies

[21]See Appendix I.C for white paper.

[22]1 cubic foot = 0.028 cubic meters

After the collapse of the Soviet Union, He was no longer considered essential for national security; hence the Helium Privatization Act of 1996 mandated that the Bureau of Land Management (BLM) sell the He reserve by 2015 at a price that would be sufficient to recover the cost of buying and maintaining the reserve, plus interest. These requirements meant that the sell-off price would be significantly higher than the market price of He at that time. The NRC study examined potential adverse impacts of the sell-off on the He market. This study, released in 2000, noted that the market had been stable since 1980 and the higher price would have no adverse effects for consumers of He. Paradoxically, however, after the sell-off began in 2000, there were significant price increases (Figure 1.7) and shortages for He users. The recent NRC study was then commissioned to examine why the earlier study failed to predict the reality on the ground and to identify measures that would allow the Federal Helium Program to respond more effectively to market dynamics.

Figure 1.7: This figure shows the impact of the He-reserve sell off on the crude He prices. The He-reserve captured a large share of the market, and set the price.



Although it is present, it is not economical to extract He directly from the atmosphere. As He produced in radioactive decay in the earth's crust migrates upwards, it gets trapped in the same geologic features that trap conventional natural gas. This leads to three sources of He production: co-production with natural gas, direct processing, and production from liquefied natural gas (LNG). The primary, and traditional, source of commercial He is co-production with natural gas.

Direct processing involves the development of He rich fields (above 0.3%), which are not viable for natural gas production. The Riley Ridge fields in Wyoming serve as an example that is independent of the Federal Helium Reserve pipeline system. The Riley Ridge facility, operated by Exxon Mobil, has a maximum He production capacity of 1.5 Bcf/year and co-produces He and CO_2 (used for injection in enhanced oil recovery).

Finally, He is co-produced in liquefaction facilities. Most components of natural gas liquefy at or above temperatures of -166 degrees Centigrade, which leaves He behind in a gaseous state (50% to 60% of remaining gas). Thus He can be produced in LNG facilities even when the natural gas has only trace amounts of He. However, this source is subject to uncertainties in the LNG market, which have no connection to He demand. Important sources of such He are Qatar, Algeria, Australia, and Russia.

The demand for He is based on its special physical and chemical properties, especially its low melting and boiling points, its chemical inertness, and its low atomic mass. It is indispensable in cryogenic applications, including creating ultracold environments to study quantum effects, and superconducting magnets used in many applications such as MRIs, particle accelerators, and laboratories studying high magnetic fields. Other applications include pressurizing and purging rocket systems, welding, and weather and party balloons. Figure 1.8 shows the breakdown of domestic uses, while Figure 1.9 shows changes in domestic consumption patterns.

Figure 1.8: This figure shows the breakdown of He use in various sectors in the US in MMcf.

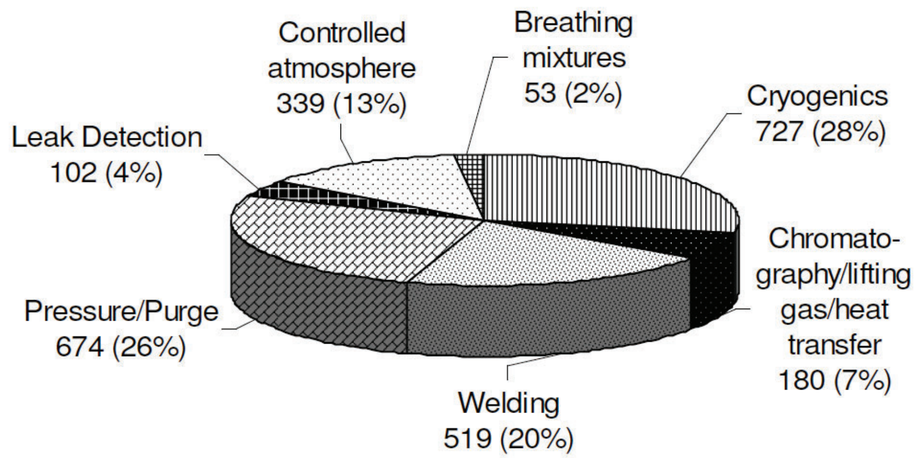
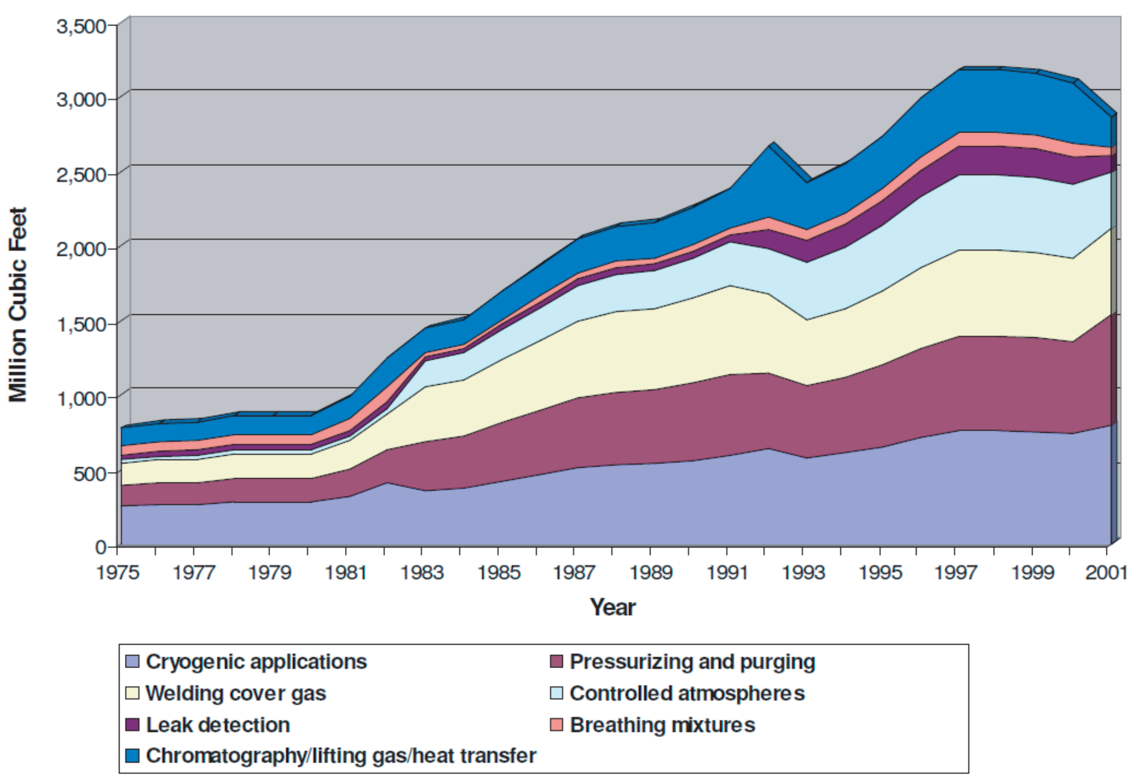
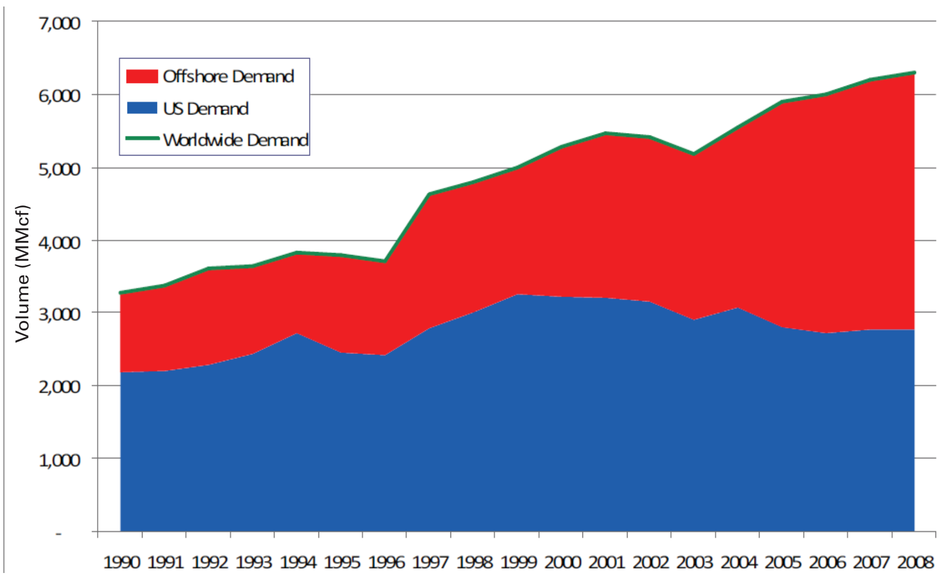


Figure 1.9: This figure shows the change in He use in different sectors in the US from 1975 to 2001.



Since 2000, He consumption in the US has remained almost unchanged due to recycling efforts by various users, especially medical MRI users. But consumption in the rest of the world has increased dramatically (Figure 1.10), primarily in industrial applications. Consequently, the US share of consumption has decreased, and will continue to decrease as demand continues to increase in Asia, according to NRC projections.

Figure 1.10: This figure shows that the world He demand is increasing, while the demand domestically has stabilized due to conservation efforts



A possible future use of He is as a coolant in new-generation nuclear reactors. He's high thermal conductivity, inertness, and the fact that it cannot be activated by neutron absorption, makes it especially desirable. It allows the reactors to operate at higher temperatures, improving their net efficiencies from 30% to 40% to as high as 50%. One design for He-based reactors employs 500 MW modules. Such a module requires 2 MMcf of He initially and 0.04 MMcf annually afterwards (to replace escaped He). If one installs 150 such units, they would meet 1.25% of current global electricity needs and require 5% of annual He to start up, and 1% per year afterwards. Scaling this technology up even further would impose significant strain on He supplies.

Dr. Lancaster wrapped up his talk by summarizing the recommendations of the NRC study. He said that their study had been received warmly, and been especially helpful in bringing attention to the effect of He price increases on small academic researchers and national labs.

Discussion

The discussion started with a question about the success of the program for recovering federal costs. Dr. Lancaster said that the price analysis had not included the revenue stream from selling the natural gas in the reserve. Given this extra revenue stream, the price was more than sufficient to cover all costs, plus interest, for the federal government by 2013.

A question was asked about Canada being a potential source of He, as it is a large natural gas producer. Dr. Lancaster said that there was not enough information available to answer that question, and there was need for an appropriate agency to collect the required data to estimate the He recoverable from sources outside the US. He added that radioactivity (from the decay of U and Th) of crustal rocks below the gas fields, which is required for He generation before it gets trapped, was highest in the mid-continent region in the US. Hence, the region was the best place for finding He-rich reservoirs of natural gas and historically has had fields with He concentrations of up to 8%.

In response to a question about the key lessons from the study of the He reserve, Dr. Lancaster said that it is difficult to predict the future, and there are always a host of unintended consequences.

A recurring theme for discussion was the impact of increasing He prices on researchers in small academic institutions and national labs. He costs are a major factor for experiments that use it as a cryogenic coolant. They also have limited flexibility to implement conservation measures to recycle the He for reuse when prices increase, because the recycling equipment can cost as much as $100,000, and research grants provide a fixed, pre-determined amount. It was suggested that grants should include funds for implementing conservation measures. It was also emphasized that these researchers represent only 2% of the He market, and most funding agencies, such as the National Science Foundation, and policy makers were unaware of the hardship they face. The NRC study has been instrumental in bringing this issue to light, and BLM is now considering ways to ensure He supply for these users.

It was noted that the Federal Helium Reserve enjoys a significant market share at present, but was also finite and would disappear from the market in the near future. Concern was expressed about the need to convey this information to industry users of He, who would face a sudden disruption when a major supplier disappears from the market.

There was some pushback from industry participants on the idea raised by Dr. Lancaster during his presentation that the welding industry had the flexibility to switch away from using He, because permitting processes take several years.

The crisis in supply of He-3 was discussed. He-3 cannot be economically produced from natural gas, and is instead artificially produced from tritium decay. An important application for He-3 is in neutron porosity detection tools[23]. The accurate estimation of porosity is extremely important for estimating oil reserves. A small error in porosity estimation can lead to discrepancies in the tens to hundreds of million barrels of oil equivalent. There is no substitute for He-3 in this application. Recently, the installment of He-3–based neutron detectors by the Department of Homeland Security (DHS), to detect unauthorized radioactive materials at ports, created a shortage of He-3. A legacy stockpile of He-3 was decimated within two years due to this new demand. Dr. Lancaster responded that the issues posed by He-3 are quite different from He-4, and the NRC study did not look into them. The price required for physical separation of He-3 from He-4 is $3,000 to $4,000/liter, which is nearly twice the current spot price of $2,000/liter. Another conference participant responded that the DHS has responded by trying to replace the He-3–based detectors with lithium-6 (Li-6) detectors, but a huge barrier was cost. Even with present He-3 costs, the Li-6 system costs 10 times more.

At the end, a question was also asked about the motivation behind the sell-off of the He reserve. Participants helped clarify that it was only due to government budget constraints, and not due to any lobbying efforts by special interest groups.

[23]See Appendix III.C for formal response by Brad Roscoe.

Summary of Key Issues and Themes

- He has special physical, chemical, and nuclear properties which make it indispensable for many applications.
- Government intervention in markets can have a host of unintended consequences.
- He, in some gas fields, is a by-product of a much larger commodity, which means that higher prices do not necessarily encourage supply increases.
- Reserves of He are not stationary — i.e., if He is not recovered at the time of production of natural gas (or LNG), it is lost to the atmosphere.
- There is limited information available on supply of and demand for He. The market is a small niche market, which increases opaqueness. An effort should be made to improve data collection and information availability.
- A small but important segment of He consumers are researchers in small academic institutions and national labs. They have limited flexibility to respond to price increases, and are disproportionately affected by them.
- Efforts should be made to protect small, but key, consumers in research from the negative impacts of He price increases.

1.4 General Discussion – Morning Program

The three morning sessions were followed by a discussion session that allowed participants to respond to and discuss all three presentations. The morning speakers had presented case studies of issues surrounding specific ECEs from varied perspectives. The discussion session began with a short talk by Dr. Kirchain on life cycle analysis and recycling, which can be found in Appendix II.B and is summarized in Section 3.2.

Epitome

The following aspects of supply of ECEs were discussed:

- There is a potential role for policy to encourage synergy among different technologies, for example, installing a solar field next to a coal plant, or recycling Pt when mitigating the environmental impacts of automotive catalytic converters. From an engineering, environmental, and strategic perspective, it makes sense to consider these components as part of the same project. However, these projects are economically complex, and difficult to capitalize, because investors like to see each component as an individual, financially self-sufficient project that needs to pay for itself; they rarely make allowance for synergies and efficiency benefits.

- While markets are not perfect, the role of government should be restricted to areas in which market enterprises cannot function effectively. These include disseminating information and funding research and development (R&D). Direct intervention of governments in markets is not advisable.

- Road maps can be effective policy instruments to foster synergies, efficiencies, and technology development. An important limitation to the "road map approach" is inflexibility. For example, the road map for the semiconductor industry[24] precluded innovative solutions that proved important but happened not to be a part of the road map. On the other hand, road maps are effective at overcoming important barriers to development, and in hindsight do more good than damage. An example of this is the photonics road map for the information technology (IT) industry.

- Price volatility has a deleterious effect on companies and technologies. Some bankruptcies in the auto industry may have been caused by price spikes of mineral commodities. This market volatility is driven by lack of communication up the supply chain.

- Industry needs a comprehensive set of strategies at the company level to address all potential calamities, such as shortages and price spikes, depending on the specific material. Strategies include stockpiling, recycling, and finding synergies with other technologies and industries.

- A major bottleneck in the supply of ECEs is the permitting of mining projects. The industry perspective is that the permitting process needs clarification and visibility. Uncertainty in the permitting process creates supply insecurity. The needed clarification and elucidation does not require regressing on environmental protection and accompanying requirements. The government should establish a uniform and transparent permitting process. This can allow industry to plan for the process and incur less financial risk.

[24]International Technology Roadmap for Semiconductors

- While recycling is important, supplies of by-products, such as Te from Cu deposits, depend on the production of established primary commodities. Until sufficient volumes of these by-products are developed in the recycling stream, it is important to maintain co-production and seek opportunities for primary production.

- Government has a significant role to play in communication between producers in the mining sector and consumers in industry. In the past, this role was informally played by the US Bureau of Mines (USBM). However, after the USBM was dismantled, the existing informal industry network that remains is insufficient. Government agencies, such as Office of Science and Technology Policy (OSTP), can play a leading role in helping to transmit supply-and-demand signals in the supply chain.

CHAPTER 2 – Afternoon Program: Policy Challenges

2.1 Substitutional Research in Physics, Chemistry, and Materials Science

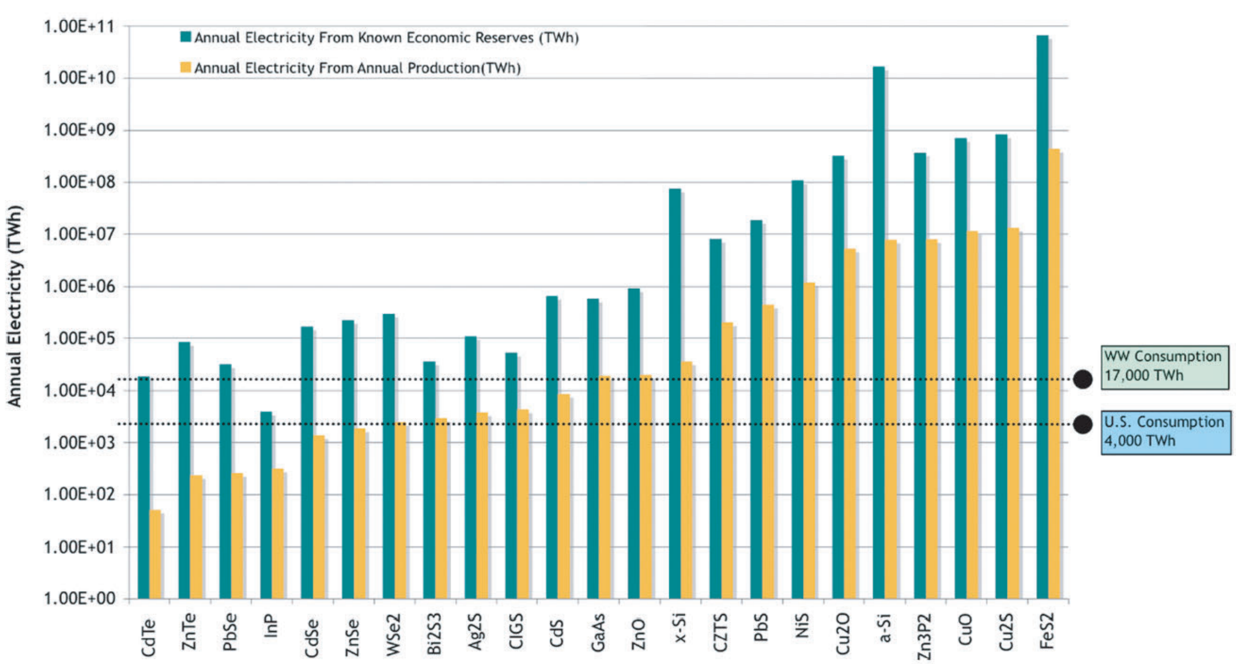
An important response to constraints on availability of materials needed for large-scale energy technology deployment is to find alternative, more abundant materials. This session focused on abundance limits, potential alternatives, and research directions for renewable energy technologies.

The keynote speaker for this session was Dr. Cyrus Wadia[25]. In his presentation titled "Mined Resource Constraints on Solar Energy and Battery Storage Potential[26]," he first analyzed the potential for novel semiconductors such as Fe and Cu sulfides and oxides, and amorphous Si in PVs, and then turned to limitations on electrochemical storage from resource constraints.

Epitome

Dr. Wadia addressed the question of materials for advanced PV technologies. He first noted that the global annual solar resource is more than four orders of magnitude greater than global annual electricity consumption, an invitation to consider large-scale PV deployment for a renewable energy future. However PVs, like many other new energy technologies, are a "materials hog." For example, one 300-mm silicon wafer of a size sufficient to power a single fluorescent light bulb can be used to create the integrated circuits needed for 500 laptop or desktop computers. Scaling up energy technologies, such as PVs, requires certain materials at an unprecedented level.

Figure 2.1: The maximum annual electricity generation potential for various PV technologies is shown in this figure, based on both known economic reserves and annual production. The horizontal axis lists the various technologies. The vertical axis shows the electricity generation potential on a logarithmic scale. The CdTe and CIGS do not have sufficient production to meet US electricity needs by themselves. The more abundant options, such as FeS_2 and CuO have several technology challenges to overcome before they can be deployed as solar PVs.

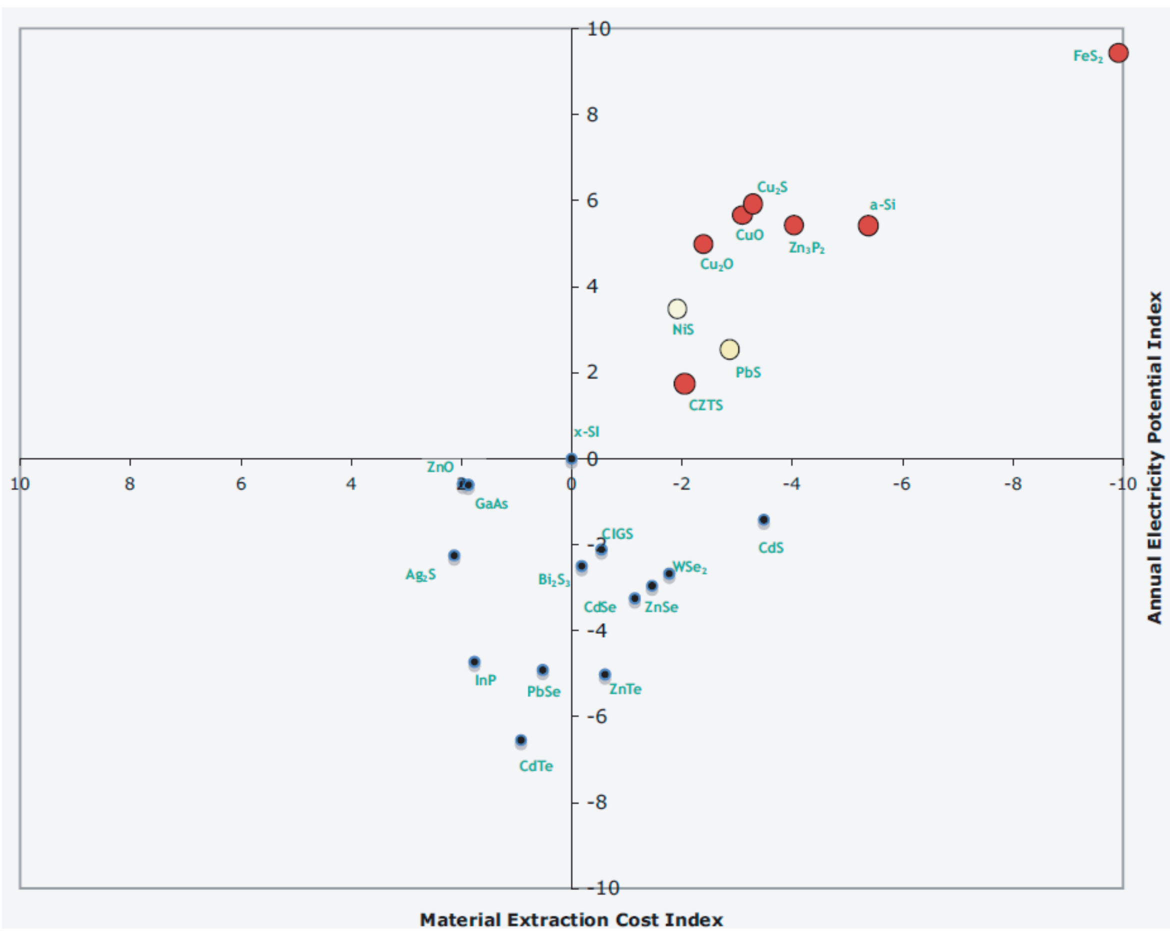


[25]Dr. Cyrus Wadia, Lawrence Berkeley National Labs (LBNL) and the OSTP

[26]See Appendix I.D for presentation.

Dr. Wadia and his collaborators[27] focused on the central issues of scale and cost for large-scale deployment of PVs. He presented the results of this study in several ways. As shown in Figure 2.1, they estimated the theoretical upper bound on scalability of 23 different semiconductors for use in PVs. For each semiconductor, the annual electricity potential was calculated assuming the theoretical efficiency set by the Shockley-Queisser limit and assuming that the PVs were constructed with the least amount of material possible. Two definitions of available material were considered: (1) the annual production and (2) the economic reserve base, both taken from the annual USGS commodity survey[28]. The annual electricity potential is shown in Figure 2.1, and the Global and US annual electricity consumption are shown for reference. Although the *reserve base for all materials is sufficient* to provide all US electricity, *current production* of two currently employed semiconductors, CdTe and ZnTe, is not. In contrast, supplies of many other semiconductors sufficient to provide global electrical consumption exist according to either definition.

Figure 2.2: The comparison between extraction cost and annual electricity potential is shown in this figure. The electricity potential is determined from theoretical efficiency and production. These values are indexed to crystalline silicon (x-Si), i.e., the values for extraction cost and annual electricity potential are divided by the corresponding values for x-Si and the natural logarithm is taken.



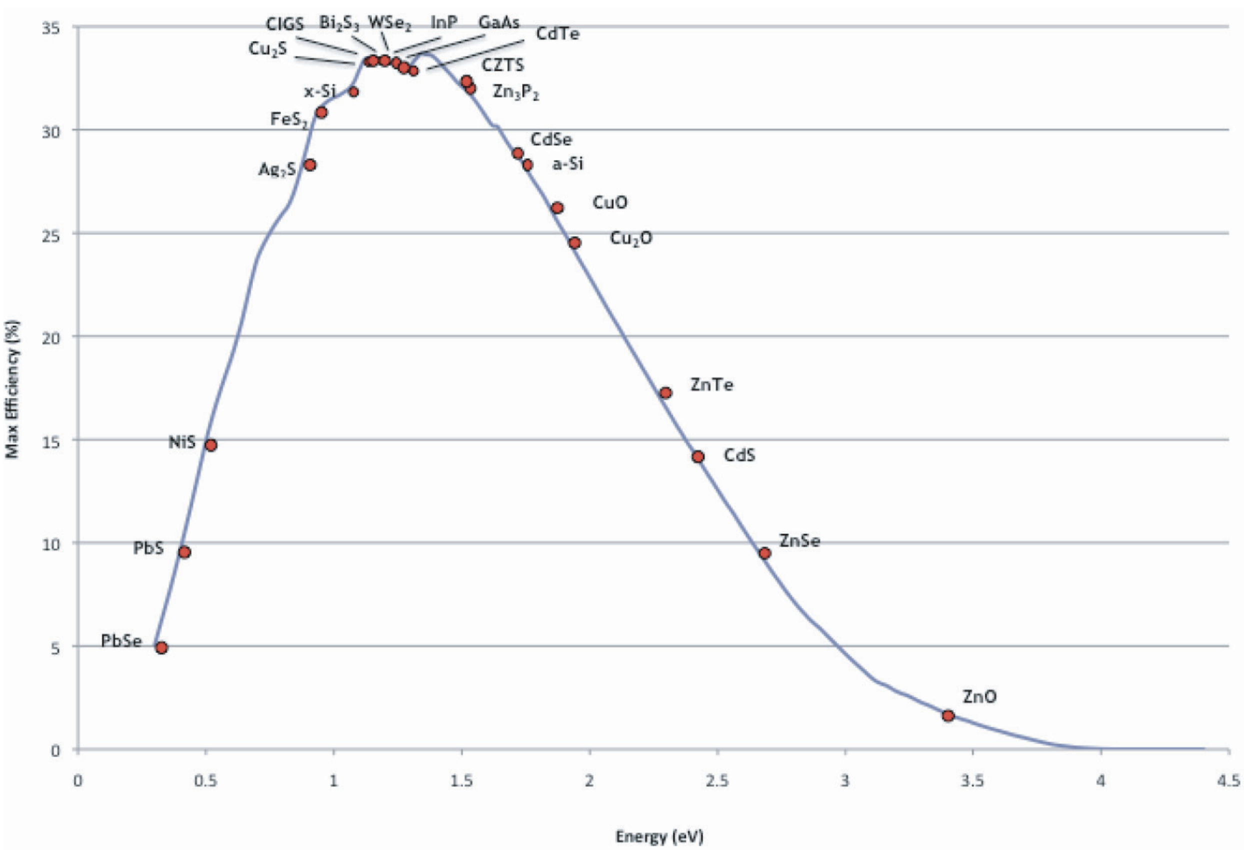
Dr. Wadia then turned to a closer examination of other, less-well-studied semiconductors. Those with the lowest material extraction costs and highest abundance are shown in red in Figure 2.2, including copper sulfide (Cu_2S), iron sulfide (FeS_2) and copper oxides (CuO, Cu_2O). He pointed out

[27]The PV scale and cost results discussed in his presentation and summarized here can be found in: C. Wadia, A. P Alivisatos and D. M Kammen, "Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment," Environ. Sci. Technol, 43 (2009), 2072–2077.

[28]Note, however, that the economic reserves, as defined by USGS, change with price and cannot be thought of as a fixed stock.

that while industry had focused on semiconductors with the highest theoretical efficiency, such as CdTe and CIGS (approximate 33%), other more abundant materials, such as FeS_2 and BiS, have only slightly lower efficiency (~31%), as shown in Figure 2.3. Dr. Wadia stressed that there are many critical material science and engineering issues like diffusion lengths, electron-hole recombination rates, and stability, which must be addressed in the development of practical PVs. He added that the purpose of this analysis was to call attention to new materials, not to take away R&D from existing technologies, nor to advocate for any particular material like FeS_2 at the expense of existing technologies.

Figure 2.3: The maximum theoretical efficiency of different PV technologies, based on the Shockley-Queisser limit are shown in this figure. While CdTe and CIGS are amongst the semiconductors with the highest efficiencies, FeS_2 and CZTS also have high efficiencies, and contain more abundant and economic elements.



Next, Dr. Wadia turned to his second example, electromagnetic energy storage, based on unpublished work on the cost and scale limitations for battery technologies. In contrast to the PV analysis, which had focused on identifying new areas for research, this study was geared towards finding resource availability limits based on the practical energy storage capacity of the batteries. Dr. Wadia's group examined 27 battery technologies that either have been shown to operate reversibly or are currently of interest in the research community. For each candidate, they determined the limiting element (see Table 2.1), defined as the element that would run out first, by computing the practical Coulombic capacity and using USGS annual production and reserves data. They found in their study that it was possible to produce one million cars from a given Li-ion–based battery technology with current annual production. However, building 100 million cars, which is 10% of the global fleet, would require increasing annual production, even though there were sufficient reserves.

Table 2.1: This table contains information about various battery technologies, including the limiting element based on annual production and reserves.

Category	Tag	Negative	Positive	Limiting Element (reserves & ann prod)	Common name	E_{theor} (Wh/kg)	E_{pract} (Wh/kg)	Additional remarks
Aqueous	1	Pb	PbO2	Pb	Lead acid	252	35	Mature technology; extensive recycling programs in place. Deep discharge causes sulfation, which lowers cycle life. Life is around 5 years.
	2	Zn	AgO	Ag		524	105	Zn shape change limits life, and dendrites are a risk.
	3	Cd	Ni(OH)2	Cd	NiCd	244	35	Mature technology. Stable and safe, with a good life.
	4	REE	Ni(OH)2	REE	Ni/MH	240	75	Mature technology. Stable and safe. Life up to 15 years depending on application and use.
	5	La	Ni(OH)2	La	Ni/MH	240	-	
	6	Zn	Ni(OH)2	Ni		372	60	Zn shape change limits life, and dendrites are a risk.
	7	Zn	MnO2	Mn	Alkaline	358	85	Currently the dominant primary cell. Zn electrode has the same problem of shape change.
Lithium ion (organic)	8	Li4Ti5O12	LiCoO2	Co		241	110	A low-energy but stable lithium-ion cell.
	9	Si (alloy)	LiCoO2	Co		861	-	The Si alloy negative electrode is currently under development. The stability and round-trip current efficiency are relatively poor.
	10	Li	LiCoO2	Li		1023	-	Li metal forms dendrites and causes shorting. Development work is focuses on eliminating dendrites.
	11	C6	LiCoO2	Co	Lithium ion	614	220	The dominant lithium-ion chemistry. Life is limited by side reactions and high temperatures; life is typically 2-3 years, but depends on application and control methods.
	12	C6	LiMn2O4	Mn		330	150	At high temperatures Mn can dissolve and limit life.
	13	C6	LiNi0.80Co0.15Al0.05O2	Li		636	250	LiNi0.80Co0.15Al0.05O2 is a "next generation" positive electrode material.
	14	C6	LiNi0.33Mn0.33Co0.33O2	Mn		646	250	LiNi0.33Mn0.33Co0.33O2 is a "next generation" positive electrode material.
	15	C6	LiFePO4	Li		385	110	LiFePO4 is a low energy positive electrode with the potential to be inexpensive and safe.
	16	C6	LiMnPO4	Mn		469	-	LiMnPO4 is an experimental positive electrode.
High temp. (other)	17	Li	S	Li		2600	350	In the high-temperature form alloy electrodes are often used, such as LiAl/FeS or LiAl/FeS2, the operating temperature is 375-500C, and the cycle life is good. An ambient-temperature cell is also under development.
	18	Na	NiCl2	Ni	Zebra	787	115	Needs special containment for high temperatures and high-purity materials. Runs at 270 to 350C to keep active materials liquid and electrolyte conductive. Good cycle life for charge and discharge.
	19	Na	S	Na	NAS	792	170	Needs special containment for high temperatures and high-purity materials. Runs at 270 to 350C to keep active materials liquid and electrolyte conductive. Good cycle life, but a limited number of thermal cycles.
	20	Mg	Sb	Sb		254	-	An experimental all-liquid battery for high-current grid-storage applications.
Flow cells (other)	21	V2O5 (3+)	V2O5(4+)	V	Vanadium flow cell	29	10	Requires a proton-exchange membrane. Upper temperature limited to 50C due to precipitation. Good life.
	22	Zn	Br2	Br		429	65	Problems with Br crossover and Zn dendrites. Uses an aqueous electrolyte and operates at ambient temperatures.
	23	Na2S2	NaBr3	Br	Regenysys flow cell	41	20	Problems with electrolyte crossover
	24	CrCl3	FeCl2	Cr		99	-	Problems with electrolyte crossover.
	25	ZnO	Ce2(CO3)3	Ce	Plurion	60	-	Uses Nafion membrane. Design may also include a Pt-Ti mesh cathode.
Metal air (other)	26	Zn	O2	Zn		866*	350	Used as primary cell in small formats (hearing-aid batteries); may be mechanically or electrically recharged. Electrical recharge is limited by the poor kinetics of the air electrode and the absence of a suitable bipolar catalyst.
	27	Li	O2	Li		3622*	-	Experimental system that uses a polymer electrolyte and an oxygen-permeable membrane. Contaminants must be kept out of the cell to prevent degradation. Electrical recharge is limited by the poor kinetics of the air electrode and the absence of a suitable bipolar catalyst.

* based on the discharge product (ZnO and Li_2O_2)

Dr. Wadia discussed battery technology performance measures, such as energy density, operating temperatures, and safety. The group concluded that according to these measures, Li-based chemistries appeared to be most desirable. He reported that according to their analysis, most battery technologies were in the range of several hundred to a thousand dollars per kWh of storage capacity. Dr. Wadia's group also did an analysis using a cost index and a performance index for batteries, similar to the one shown in Figure 2.2 for PVs. They found that while some compounds, such as NaS, lead to a lower-cost battery, the cost of the finished system was similar to alternatives with higher material extraction costs. He concluded by noting that there was need for further R&D for less-well-studied battery storage chemistries involving Na, S, Mg, and Zn because they had lower material extraction costs.

Dr. Wadia did not spend much time discussing battery storage of energy at the grid level, because it is less economic compared to pumped hydro or compressed-air storage, even though it may be needed with a larger deployment of intermittent electricity sources.

Discussion

The discussion focused on the comparative analysis of batteries. It opened with a question on transferring from one battery technology to another. Dr. Wadia replied that unlike PVs there is some fungibility. For example, experience with Li-based batteries is transferable to Na-based chemistries.

There was a discussion regarding the feasibility and timeline for large-scale deployment of electric cars. It was noted that due to infrastructure considerations, and the disruptive nature of plug-in hybrid electric vehicles (HEVs), it may be 25 to 30 years before 100 million electric cars might be deployed. Dr. Wadia responded that he thought the time scale may be closer to 75 years.

Dr. Wadia was asked whether studies such as his should inform national security policy makers. He responded that while they might and while there are various initiatives currently under way in the Department of Energy (DOE) and the Department of Defense (DOD), he believed it was more important that they be used to stimulate R&D and further public interest.

Discussion turned to the importance of R&D on international competitiveness. One participant asserted that it would be possible to reduce the extraction cost of Nd by half. Another participant said that the US was the largest producer of steel after World War II. Although that has changed today, the US has developed improved and advanced technology for steel production, while China continues to use old technology. Better technology makes the US competitive even though China has lower labor costs.

The discussion then turned to grid storage. It was pointed out that pumped hydro and compressed air are also capacity limited, even though they are cheaper than battery storage. The environmental impact of pumped hydro makes it nearly impossible to develop new sites in the US. Dr. Wadia said that it is difficult to do a fair comparison of pumped hydro and compressed air storage.

A participant wondered whether batteries had a role to play in stationary storage for grid fluctuations at time scales shorter than the day/night fluctuations associated with intermittent resources. In response, another participant noted that the high cost of stationary storage makes it cheaper to use demand-side management to temper these fluctuations. Also, experience shows that in countries where there is large deployment (10% to 15%) of intermittent sources, backup natural gas generation is built to compensate for the fluctuations.

Concerns about national security were reiterated by one participant, who noted the absence of Li battery production and urged for the extraction of the required resources in the US. In response, others noted that an argument could be made for "stockpiling" the resources in the ground for the future, since the international market now provides these materials at a cheaper cost. Another countered with the example of battery production by Saft for defense purposes, indicating an onshore capacity for R&D.

Another participant continued the discussion about national security by noting concerns about China's dominance. China currently controls 17 key elements needed for technology development, and they are withholding exports, focusing instead on importing technology. They may start restricting other elements, as in the case of Antimony (Sb), which is used in flame-resistant sleepwear for children. Actions like these represent a significant threat to national security.

Finally, Dr. Wadia was asked in what other areas cost and scale analyses might be applied. He responded that there were many potential areas for applying analogous analyses grounded in materials science, one example being thermal electrics. Other possibilities include pumped hydro and compressed air storage. He briefly noted that there is much old and often fragmented, but potentially very useful, research on materials. Finding and integrating this information and making it accessible presents a significant challenge in information dissemination.

Summary of Key Issues and Themes

- Elements and materials required for energy technologies have applications in other technologies, such as computers, which compete for supplies.
- Energy technologies can be materials intensive — a "materials hog."
- Other potential semiconductors for PV applications exist with favorable extraction economies and theoretical efficiencies. They need more R&D to overcome practical challenges.
- Development of these potential new technologies, however, should not occur at the expense of use and development of existing technologies.
- While there are sufficient reserves in the ground to meet projected needs, large-scale deployment would require increases in annual production for most PV and battery technologies.
- There are concerns about monopoly and access restriction by China, because of their dominance in the production of several key elements needed for new energy technologies.

2.2 Tracking Critical Elements in the US

Any substantial discussion of elements critical for new technologies must rely on data on production, both from primary sources and recycling, and consumption mechanisms and dynamics. This session addressed the issues and concerns regarding these data.

The keynote speaker for this session was Mr. Scott Sibley from the USGS's Mineral Information Team. Mr. Sibley, in his talk titled "Supply and Demand for Selected Energy Related Mineral Commodities[29]," discussed the important factors affecting supply and demand of mineral commodities, and the USGS's role in collecting production and consumption data to understand these factors. He used Cd, Li, REE, and He to illustrate issues of interest to the APS/MRS study and the workshop participants.

Epitome

Mr. Sibley began his presentation with a review of supply-and-demand economics for mineral commodities. He identified and defined accessible components of supply, which include primary, secondary, and existing stocks. Primary supply comes from mining activities, including by-products (which he also called secondary products or co-products); secondary supply comes from recycling both new and old scrap; and existing stocks include producer, trader, exchange, and consumer stocks. He focused only on primary and secondary supply.

Mr. Sibley emphasized that the supply outlook for mineral commodities, which have seen a dramatic growth in use, can be impacted by many factors, including price, rate of consumption, production capacity, recycling, substitution, rate of discovery, environmental regulation and land-use issues, and finally costs of exploration, mining, and processing including energy costs. All these factors are interdependent, and vary from one commodity to another. However, for secondary products, price increases have little impact on increasing supply volumes. Additionally, bringing new supplies online requires long lead times of 5 to 15 years, which can cause short-term bottlenecks.

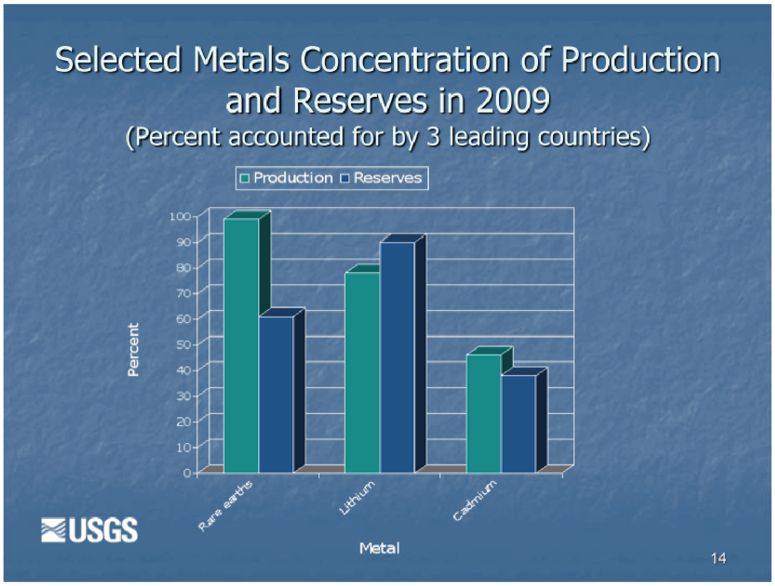
He stressed the fundamental importance of crustal abundance and form of mineralization to the production of a given mineral. Of course, production of minerals is higher for those with higher crustal abundances. The location and form of mineralization, which determines characteristics such as amount of overburden and waste rock, and tonnage and grade of ore, impact the decision to develop a deposit. Additional challenges exist for secondary products. In the case of Te, supply may be inhibited due to increasing use of technology that leaches Cu from certain types of ores followed by solvent extraction and electrowinning of a high-purity Cu product, whereas the alternative method of refining via electrolytic processes allows for Te co-production. Extracting Te when electrowinning presents a significant metallurgical research problem.

Mr. Sibley went on to point out that the volume of reserves (the economically recoverable resource) depends on assumptions about what is considered economic. As price increases, the grade of ore required for development decreases. This in turn increases the reserve estimate. He illustrated this point with data for estimates of molybdenum (Mo) reserves in the Yorke Hard Deposit in Canada as a function of cutoff ore grade. He also presented data on reserves to production ratio (R/P) of several elements, with REEs having an astounding R/P of 800 years, which is more than 8 times that of iron. He also noted that data on reserves and production volumes for many of the elements of interest to the workshop and POPA study from public sources, such as the USGS, was limited either due to unavailability (e.g., world He reserves) or withholding

[29]See Appendix I.E for white paper.

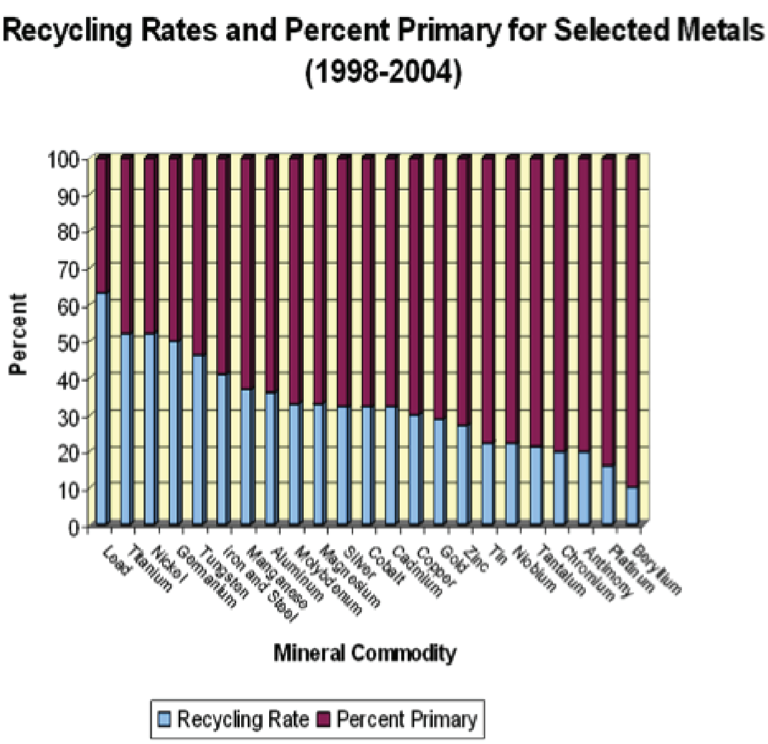
requirements for confidentiality (e.g., Te). To illustrate the impact of available data, Mr. Sibley showed that reserves and production of REEs, Li, and Cd is highly concentrated, with the top three countries containing the bulk of the reserves and production, as shown in Figure 2.4.

Figure 2.4: This figure shows the concentration of production and reserves of REEs, Li, and Cd in the leading 3 countries.



Metals can be recycled repeatedly because most uses are nondestructive. This makes recycling an important supply source. Recycling has many benefits, as it not only reduces depletion of the resource but also decreases the environmental impact from land use and pollution from refining activities. Because of its toxicity, Cd is a particularly good candidate for recycling. This represents an opportunity as Cd has only a 30% recycling rate[30] and 15% recycling efficiency[31] (Figures 2.5 and 2.6). The USGS has conducted recycled materials flow studies of 26 metals, which are available online on the USGS Web site. Mr. Sibley briefly discussed the flowchart for cobalt (Co) from such a study.

Figure 2.5: The recycling rates of different metal commodities are shown in this figure.

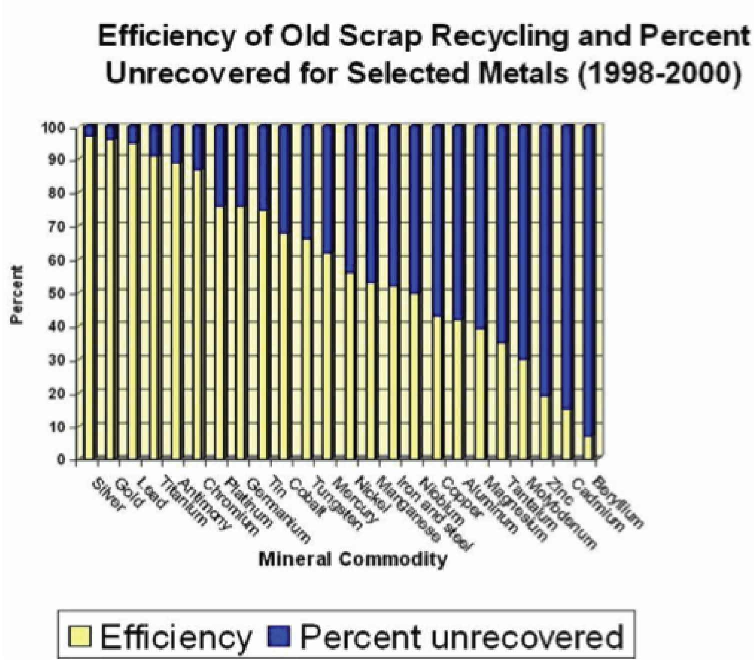


Mr. Sibley presented USGS data on production of Cd, which showed that production had increasingly shifted to Asia from Western Europe and the US. China, Republic of Korea, and Japan accounted for 50% of 2009 production. Currently 80% of Cd is produced as a by-product from processing and refining of Zn ores and concentrates, and the rest is obtained from recycling facilities in France, Germany, Sweden, Japan, and the US. Consumption of refined Cd, on the other hand, was increasing in Belgium and China while declining in the rest of the world. The biggest share of consumption is by NiCd batteries (83%). Cd is also consumed in the production of pigments, coatings and plating, stabilizers of plastics, nonferrous alloys, PV devices, etc.

[30]Recycling rate is defined as the quantity of recycled old and new scrap as a percent of apparent supply. Old scrap refers to post-consumer scrap and new scrap is material returned from the manufacturing plant which has not been used.

[31]Recycling efficiency is the quantity of recycled old scrap as a percent of old scrap available for recycling, where old scrap is post-consumer scrap.

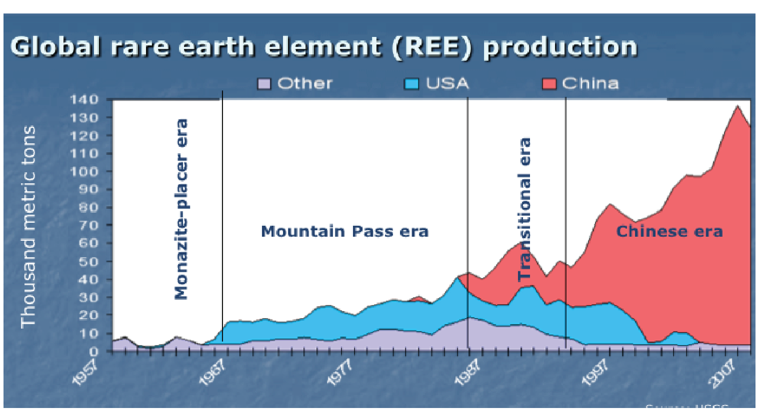
Figure 2.6: The recycling efficiency of various metals is shown in this figure. This suggests that there maybe significant potential for recycling metals such as Cd, while other metals, such as Pt, are recycled almost completely.



Turning to Li, Mr. Sibley said that Li is found in either hard-rock ore deposits or brine deposits. Chile, the largest Li producer in the world, has brine deposits, while Australia, the second largest producer, has hard-rock deposits. Li consumption has been growing steadily in the world, while declining in the US. After ceramics and glass, Li batteries are the second largest consumers of Li, and their share is expected to grow in the future, in part due to use in HEVs.

Mr. Sibley also discussed the production of REE's in the world over the last 50 years. REEs are recovered mostly from bastnaesite (China and US) and monazite. They are not actually rare and there are many unexamined carbonatites, laterites, pegmatites, and specialized granites as potential future sources. He pointed out that not only has the production of REEs increased, but it has moved from Mountain Pass, CA, the dominant source from 1967 to 1985, to China, where 97% of all REEs are currently produced (Figure 2.7). He asserted that the Chinese were trying to decrease supply in an effort to increase prices of REEs. On the demand side, Mr. Sibley noted that REEs are used in a number of diverse, high-tech, and environmental applications, where substitutes are either inferior or lacking altogether. These applications include nickel metal hydride (NiMH) batteries for HEVs, permanent magnets, and automotive pollution control catalysts. Expected growth in these applications will increase demand for REEs. For example, the amount of REEs in NiMH batteries for HEVs is expected to double in the next 4 to 5 years.

Figure 2.7: The production of REEs has increased dramatically over the last decade, however it has shifted from Mountain Pass, CA, to deposits in China. China now produces 97% of REEs globally.



For He, Mr. Sibley briefly noted that while the production of He had been quite flat since 2005, consumption in the US had declined while exports increased.

Mr. Sibley concluded his talk by reiterating that higher prices lead to increases in reserves due to increased exploration. But the long lead times of 5 to 15 years mean that there is a potential for short-term supply shortfalls. He noted, based on the data he had shared, that there were significant opportunities for increasing supply from recycling, depending on the metal (Figures 2.5 and 2.6). He also noted that while there were sufficient reserves to support current rate of consumption for REEs, delays in planned production coming online could lead to REE supply problems.

Finally, he invited everyone to visit the USGS at their Web site for data, statistics, and recycling studies at http://minerals.usgs.gov/minerals.

Discussion

The discussion session began with two formal responses, the first by Mr. Marc Humphreys from the Congressional Research Service (CRS), and the second by Dr. Diana Bauer from the Department of Energy's Office of Policy and International Affairs[32].

Mr. Humphreys informed the participants that CRS responds to 800,000 queries yearly from Congress, and they rely heavily on USGS data to fulfill this task. With regard to the issues being discussed here, they receive questions that can be grouped into three categories. The first category concerns import dependence, the second concerns federal land use, and the third concerns stockpiles and the role of Congress in ensuring and securing supply. He shared several examples of such questions, and then asked whether the funding for the Minerals Information Team, under the Minerals Information Act, was sufficient. He noted that the appropriations for the Minerals Information and Assessments in the USGS had been fairly constant over the recent years (approximately $50 million/year overall, of which $15 million/year is for the Minerals Information component), compared to the Energy Information Agency (EIA), with a budget of approximately $200 million/year.

Dr. Bauer, DOE, Office of Policy and International Affairs, talked about new initiatives at DOE. DOE has recently announced a new materials strategy for energy. They are relying on data from the USGS regarding supply. The EIA is doing a demand-side analysis — looking at wind, PV-solar, and electrical vehicles. They expect to come up with a research strategy for the whole supply chain, including mining. It is possible that they will also look at economic factors, stockpiling, and discussions with other countries. They plan to issue a public request for information in early May of 2010.

During the discussion, there was also a presentation by Ms. Dayan Anderson. A summary of her talk and the associated discussion can be found in Section 3.1.

One participant inquired about the accuracy of the data used for constructing the R/P ratios and shared the information that in a commercially maintained database, there were over 2,000 deposits listed of which only five were commercial. A concern was expressed that such numbers (R/P of 800 years for REEs) produce a false sense of security, especially when the data may include noncommercial deposits. An additional comment was made that generally the reserves for primary products, such as iron, were underestimated, while for secondary products, such as REEs, were overestimated. Mr. Sibley responded that only deposits that are producing or are likely to start production in near future are included in reserves — that is, reserves by definition only include economically viable deposits. He also noted that the notion of a reserve base, used by the keynote speaker in the earlier section, Dr. Cyrus Wadia, was a useful one, as it conveys potential volumes that would be producible due to technological advancements (lowering the cost of production) or price increases (making marginally economic deposits economic). He expressed regret that estimates of reserve base were being discontinued by the USGS this year, because they did not have the resources needed to construct such estimates.

[32]See Appendices III.A and III.B.

To a concern about the accuracy of reserves and production data for China, Mr. Sibley responded that they have a country expert for China, and while he feels less confidence in these numbers compared to other countries, his confidence had improved over time. Another participant shared an anecdote to illustrate the unreliability of Chinese data and added that when they were investigating about a dozen commodities, they found China's reserve numbers were overstated for mineral commodities that they imported because they use lower cutoff grades. On the other hand, their reserve numbers were understated for minerals they were exporting. At this point, one of the participants pointed out that the definition of reserves was an arcane and complex subject, on which the United Nations has strived for many years to achieve consensus and convergence. Also, at various points during the discussion, other participants expressed concern about China's increasing role in the production of ECEs, and its implications for US national security.

One participant asked if the USGS was planning to update Professional Paper 820 (produced in 1973), which contained extensive and authoritative data about US and global mineral resources, reserves, and inferred reserves — in other words, the reserve base. Mr. Sibley responded that this professional paper was still used within the USGS Minerals Information Team, as geology does not change that quickly. However, they do not have the resources at present to carry out the extensive work needed to publish an update to this influential paper. At this point participants in the workshop expressed their concern for the need to provide the USGS with the necessary resources to fulfill its obligations for collecting data and conducting estimates of reserves and the reserve base of ECEs.

Summary of Key Issues and Themes

- There is a need for transparent and accurate data of production, reserves, and reserve base for ECEs.
- Higher prices increase reserves; however, reserves and production for some key elements, such as REEs, are concentrated geographically.
- Long lead times of 5 to 15 years can cause shortages and price spikes in the short term.
- China has emerged as a primary producer of ECEs because of significant resources, less stringent environmental regulations, and lower labor costs.
- Scrap and recycling present significant sources of supply in the short term, while substitution occurs over longer time scales.
- The definition of "reserves" and "reserve base" is imprecise and nonuniversal, making estimates of available resources difficult to quantify.
- USGS is constrained by resources and cannot conduct a comprehensive estimate of the reserve base for ECEs.

2.3 Materials Policies of Other Nations

Mineral resources are distributed unevenly around the globe. Transnational political concerns have motivated some nations to develop national strategies for mineral-resource security. The need to consider a national strategy has been highlighted by relatively recent emergence of China as a dominant supplier of several elements that are critical for new energy technologies. Nations like Korea, which have limited mineral resources, have different approaches than nations like Canada, which are mineral rich. This session focused on presentations by mineral experts from Korea and Canada. The keynote speaker for this session was Dr. Jung-Chan Bae[33]. In his talk titled "Strategies and Perspectives for Securing Rare Metals in Korea[34]," he discussed the Korean government's approach to ensuring materials supply security. During the discussion session, Dr. Leonard Surges highlighted some key components of Canadian national policy (see Section 3.3).

Epitome

Dr. Bae framed his talk by observing that human civilization has moved beyond the Steel Age and into the Age of Rare Metals. He compared Korea with its two close neighbors, Japan and China, which provide striking contrasts in terms of natural resource endowment, industrial development, and recycling efforts with respect to rare metals. Korea has limited natural resources, limited mineral-supporting industry, and weak recycling. He stressed the importance of a production stage intermediate between extraction and the production of finished products in which raw rare metals are converted into refined materials and alloys. He referred to this stage as *materialization*. Typically, Dr. Bae reported, rare metals are imported from China by Japan. After materialization in Japan, Korea imports these highly refined materials, manufactures finished products, and either exports or consumes them. After use, the waste is either lost or goes back to China and/or Japan. Japan recycles the materials and exports them again to Korea. One of the principal goals of Korea's rare metals strategy is to design policies that will make Korea self-sufficient by recycling rare metals.

The process described by Dr. Bae began with the identification of 56 "rare" elements, subject to instability in supply and price fluctuations. These aspects are illustrated in Figure 2.8. The rarity is normalized to steel. The platinum group metals[35] (PGMs), for example, are 23 million times rarer than steel. The instability of supply is higher for elements whose production is concentrated in a few countries. The supply of REEs, for example, is unreliable because 97% of annual production takes place in China. A subset of 11 of the 56 elements (counting REEs and PGMs each as one) were identified as strategic critical elements[36] (SCEs). The heart of Dr. Bae's talk was a detailed discussion of Korea's policies for limiting supply risk for these SCEs. These policies cover four major areas: (1) securing natural resources; (2) enhancing R&D for materialization; (3) circulation and recycling; and (4) establishing infrastructure for development of the rare metal industry.

[33] Dr. Jung-Chan Bae, Korea Institute of Industrial Technology (KITECH)

[34] See Appendix I.F.

[35] PGM consists of six elements, namely ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and Pt.

[36] The SCEs are REEs, Si, magnesium (Mg), Ti, tungsten (W), PGMs, Ni, Zr, In, lithium (Li), and Ga.

Figure 2.8: The correlation between rarity, supply instability, and unstable prices is explored in this figure. The SCEs are rare compared to steel. The first table on the left shows that the crustal abundance of PGMs is 23 million times less than the crustal abundance of steel. The middle table shows the market share of global production in the leading producer country. China dominates the production of more than half of the SCE. This concentration means that supply is unreliable. Rarity and unstable supply contribute to the price variations shown in the table on the right.

Rarity → **Unstable supply** → **Unstable price**

Element	Resource Rarity*
PGM	23,000,000
In	3,800,000
Se	1,200,000
Cd	250,000
Bi	240,000
Sb	180,000
Ta	66,000
W	33,000
Sn	29,000
Ge	17,000

* Exhaustion rate of steel =1

Element	1st Product Country	Share
REE	China	97.1
Nb	Brazil	89.8
W	China	86.5
Sb	China	81.6
Ta	Australia	62
B	Turkey	58.7
PGM	South Africa	58.6
Si	China	57.7
In	China	54.8
Bi	China	52.5

Element	$/ton (2002yr)	$/ton (2007yr)	Price Variation (%)
Se	8267	72222	774
Mo	8840	70260	695
In	87140	680800	681
Ni	6772	37181	449
Bi	6658	31437	372
W	5400	24826	360
V	9662	43295	348
Co	15719	64440	310
Cr	717	2761	285
Ti	5980	22530	277

Dr. Bae explained that the Korean government was attempting to secure supply both domestically and overseas. For overseas supplies, Korea was actively gathering information and dispatching investigation teams to explore potential resources, forming strategic alliances, such as KCMIC[37] with China, participating and investing in mine developments, and modifying regulations that would encourage investments in foreign developments related to rare-metal resources. On the domestic front, Korea actively stockpiles 21 elements to cover 60 days of domestic demand. These policies range from the immediate short term (stockpiling) to the long term (exploration and development).

Dr. Bae discussed the steps being taken to further R&D in materialization of rare metals. Having chosen 11 SCEs, based on rarity, instability, and concentration of supply and demand, Korea went on to identify 40 technologies on which to focus their R&D efforts. They have developed road maps for these metals and associated technologies. For metals with technologies that have long been commercialized in Korea, such as In and PGM, the road maps focus on establishing and enhancing R&D collaboration between producers and consumers. For metals that have had no prior commercialization in Korea, such as Li, REEs, and Ti, the government is taking the lead in establishing the needed capital-intensive R&D projects and associated industries. These technologies, on which Korea intends to spend $300 million in 10 years, can be grouped into four categories: resource extraction (refining and smelting), materialization (processing and treatment), alternative resources (recycling), and substitution and use-reduction[38].

[37]Korea-China Material Industry Committee

[38]They plan to invest $49 million in 7 technologies for resource extraction (refining and smelting); $81 million in 16 technologies for materialization (processing and treatment); $100 million in 7 technologies for alternative resources (recycling); and $70 million in 10 technologies for substitution and use-reduction.

Dr. Bae emphasized the significant role recycling can play to address supply-security considerations, and referred to it as an *alternative resource* as opposed to a *natural resource*. The main goal for recycling is to increase the national efficiency of materials use. The main targets are scrap generated during manufacturing of materials and products, and products that have reached their end of life and would otherwise end up as waste. He noted that recycling scrap during the manufacturing process was more cost-effective than after the fact. He conceptualized recycling rare metals from waste streams, such as computers and other electronics, as a mining operation and dubbed it *urban mining*. Urban mining requires collection, separation of recyclable objects, and reprocessing.

He stressed that urban mining required activation and maintenance of the circulation of rare metals in the recycling system. A successful implementation of an "urban mining strategy" will require appropriate regulation of the system, effective and efficient collection of recyclables, and increased awareness of the recycling potential of consumer products using a system to indicate the use of materials of interest. He indicated that they have already implemented such a system, called *Rare Metal Indication System*, for six SCEs used in IT products such as cell phones and digital cameras.

The last part of Dr. Bae's presentation focused on the strategies that have been adopted by the Korean government to establish infrastructure in support of their rare-metal industry. Three concrete organizational actions have been implemented. The first is the formation of a Rare Metal Industry Governing Committee that advises the government on policy matters and has members from industry, academia, and the South Korea Ministry of Knowledge & Economy (MKE). The second is the establishment of Korea Rare Metals Center (KRMC) at KITECH that makes selection and funding decisions for technology projects for strategic rare metals, and provides oversight of R&D programs. And the third is the institution of local Rare Metal Commercialization Centers focusing on particular rare metals. Three such centers[39] have been established so far. Dr. Bae, who is the director of KRMC, highlighted its role in coordinating government, local universities, and small and medium enterprises to facilitate R&D support for core technologies, carrying them through to commercialization, and establishing new industry, especially small and medium enterprises.

Dr. Bae pointed out that an important part of the strategy to develop infrastructure and R&D support was to incubate selected industries, until they are securely established, by providing investment funds and tax incentives. As part of this effort, Korea Resource Corporation (KORES), a government enterprise, plans to invest $820 million in new rare metal specialized companies. He mentioned that he and his colleagues were attempting to set up a database to monitor rare metals materials flow. They were also investing in developing workforce expertise by funding graduate students in rare metal technologies, and by establishing international collaborations.

Dr. Bae concluded his talk with a discussion of the ambitious goals set for Korea to secure its supply of SCEs, for 2018 relative to 2009: increasing self-sufficiency in materials from 12% to 80%, increasing their technical level from 60% to 95%, and increasing the number of specialized companies founded from 25 to 100.

[39]The center in Kang-won province will focus on Mg and Ti; the center in Choong-Cheong province will focus on In and Pt; and the center in Jun-nam province will focus on Mg and Ni.

Discussion

The discussion began with a question about the details of the road maps, whether there was one road map for several technologies, or separate road maps for each technology. Dr. Bae responded there were going to be three new projects this year, focusing on Li extraction, Pt recycling, and Co recycling. And over the course of 10 years, there would be a total of 40 such projects. From Dr. Bae's response, it appeared that he used the words projects and road maps interchangeably.

The next question addressed to Dr. Bae probed the motivation for efforts discussed during his presentation. He responded that the Korean actions were motivated by Chinese export restrictions, both real and threatened. These restrictions started three years ago, and his office took the lead in organizing a review of the situation. He also noted that there is an effort to enact legislation to protect their work from policy changes that may arise from changes in government.

One participant asked Dr. Bae about the details of the policies and regulations surrounding stockpiling. The questioner pointed out that stockpiling by governments usually tends to have the opposite effect to what was intended, exacerbating price swings due to shortages and surpluses by buying during a shortage and selling when there is a surplus. Dr. Bae responded that the Korean government had historically stockpiled metals such as Zn, Cu, and Al, at levels of 20 days of demand. As part of their strategy to address their concerns for rare metals, they had increased the stockpile volumes for the 11 CSEs to 60 days of demand.

Another participant inquired whether the road maps were developed with significant industry input and participation. Dr. Bae said that, while they had contacts within the industry, the road maps were developed internally by him and his colleagues at KRMC.

Dr. Bae was also asked whether they had an organization similar to the USGS's Mineral Information Team. He replied that although they do not, they would like to establish an equivalent.

Summary of Key Issues and Themes

- Ensuring supply of rare metals, especially SCEs, is a priority for the Korean government.
- Materialization, i.e., the establishment of industry to produce finished materials for use in consumer products, is an important component of their strategy.
- Recycling has the potential to emerge as an alternative resource.
- An efficient and comprehensive system is needed to realize the full potential of recycling as an alternative resource.
- A robust structure is needed for R&D support by the government and the development of suitable industries and enterprises. This role is played by KRMC.

2.4 General Discussion – Afternoon Program

In a format similar to the morning, this discussion session focused on the three afternoon presentations. The conversation focused on issues of government role and policies; recycling R&D and consumer participation; human resources; and international trade and national security risk.

Epitome

The following questions and issues were deliberated by the participants of the workshop:

- The discussion session began with a short description by Dr. Ian Turnbull of his and Dr. Graedel's research on developing lower bounds for estimates of known reserves of Co. In a meta-analysis of peer-reviewed published data, they had surveyed 32 different Co-bearing deposits to arrive at a lower bound estimate of less than 7 million tons (Mt) of Co, as compared to the Mineral Information Team (USGS) estimate of 13 Mt. Their methods and criteria contrast with those employed by the USGS. After completing the Co study, they plan to focus on In, Ga, Te, and Se. Their preliminary survey of data suggests that In supply will be quite limited.

- There was a summary of recent activities at the OSTP regarding critical elements. OSTP is particularly well suited to bring together all the agencies and stakeholders to address this multidisciplinary and interagency issue. OSTP has used the White House's convening power to hold a joint meeting on the issue of REEs with representatives of the Departments of State, Interior, Commerce, Defense, and Energy, as well as the Environmental Protection Agency (EPA), US trade representatives, the Council on Environmental Quality (CEQ), and the Office of Energy and Climate Change (OECC) from within the White House. The USGS — a scientific institution that is policy neutral but policy relevant — provided information on applications of REEs in various technologies, especially defense related. This meeting resulted in the formation of a working group and will probably lead to a 10-year National Science and Technology Program (NSTP).

  However, the long-term continuity of these efforts cannot be guaranteed. Currently, there is no legislative framework that protects OSTP's work, but history suggests that even the presence of legislation does not guarantee that the activity will survive a change in political leadership. The issue of REE and other ECEs requires sustained, long-term policy support, because of the timescales involved in R&D and deployment.

- Existing government supported R&D has gaps and needs expansion. The DOE is currently engaged in an effort to coordinate its funding programs across its various offices, including Office of Science, Advanced Research Projects Agency-Energy (ARPA-E), and Energy Efficiency and Renewable Energy (EERE). At present, a comprehensive picture does not exist.

  A critical area for expanded funding is manpower development in areas such as mining engineering. Currently, there is no government-sponsored graduate support in this discipline, perhaps, it was suggested, because of a feeling that if industry considers it important, industry will fund it.

  Several other areas were mentioned where research funding is needed. Research that is neither basic nor focused on immediate practical application was mentioned, with magnetic refrigeration as an example. Other examples included life cycle analysis and behavioral science research with direct bearing on recycling.

- There was discussion of research support focused on secondary production. A participant pointed out that there is limited awareness, not only in the public, but also in the academic and research community of the significant role recycling can play in mitigating supply, security, and environmental risks. It was stated that ARPA-E has signaled to researchers that it does not consider recycling as an interesting area of research. The Minerals Resources Program at the USGS has limited funding for research support, though it has provided a grant for the study of product lifetimes at Yale, which is relevant to recycling. This situation in the US is in marked contrast to the Korean proposal, described by Dr. Bae, to spend $100 million in 10 years on research focused on recycling and urban mining.

- A successful recycling program needs consumer participation and reliable information on the characteristics of the waste stream to shape an effective strategy. However, gathering the necessary information can appear to be government intrusion into the lives of private citizens. There is a need for balance between privacy and the public good.

- The meaning of the phrase “substitutional research” needs clarification. In the context of this workshop it is intended to refer to areas of basic and applied research which will lead to technologies with more sustainable and cheaper supplies. However, this term may be interpreted differently, raising concerns about the unintended consequences, including reduction in efficiencies, that arise when one material is substituted for another in a technology without sufficient forethought. It can also be interpreted at a larger scale where one system is replaced by a different one, such as HEVs substituting for gasoline engine cars.

- Efforts for addressing various concerns discussed in this workshop would benefit greatly if an overarching framework can be designed that assigns a meaningful and quantifiable value to various elements and technologies. Korea has constructed such a framework, and it appears to provide a direction and focus for their efforts.

CHAPTER 3 – Supplementary Presentations

3.1 A Communications and Outreach Perspective

Critical decisions involved in the development and husbandry of mineral commodities are affected by public perceptions of their scarcity, their critical importance, and the sheer scale of their use. Ms. Dayan Anderson[40] gave a short presentation to highlight the need for educating the public about society's mineral footprint, and the challenges to effective communication presented by the complexity of the subject[41].

Epitome

Ms. Anderson began by noting three complex problems that need to be addressed in communications with the public. First, finding succinct language to express the complex issue of mineral use and availability effectively, and to raise the public's awareness without tremendous over-simplification. Second, balancing the use of materials around the world to eliminate waste and to raise more people to at least a subsistence level. And third, to develop tools and visualizations to educate the public about the rare elements and critical materials in ubiquitous devices such as cell phones.

Ms. Anderson began by noting that the situation regarding critical minerals is complex, with many nuances and caveats. Capturing the public's interest and attention for a complex discussion presents a significant challenge. What terminology and language should be used? How can society be moved along a learning curve analogous to the one followed by the environmental movement? Ms. Anderson noted that early environmental writings, such as Aldo Leopold's *A Sand Country's Almanac* (1949), used simple images to convey complex concepts. Leopold wrote of the "… spiritual dangers in not owning a farm. One is the danger of supposing that breakfast comes from the grocery, and the other that heat comes from the furnace." Ms. Anderson suggested that we need to carry this reasoning further and point out the "spiritual danger" in thinking that the axe that felled the tree and the bricks for the furnace come from the local hardware store.

She observed that the public's awareness of environmental issues was much further along than its appreciation of rare materials. There is much work to be done to raise awareness not only of material use, but also of its connection with environmental concerns, and with our socioeconomic well-being. To achieve this, she suggested extending the concept of the environmental footprint to a "material footprint." Concepts like a mineral, chemical, and energy footprint should be perceived on the same footing as more familiar concepts like an ecological, carbon, or water footprint.

She stressed that a discussion of mineral availability has five key areas to cover: geologic availability; technical availability; environmental and social constraints; the role of government for managing resources through policy and its influence; and economic feasibility.

Finally, Ms. Anderson described an ongoing project to create Web tools to convey to the public what materials are used in an everyday device — a cell phone, for example — by adapting the idea of a footprint from the environmental movement. She encouraged the participants of the workshop to keep communications and education in mind as they proceed with their work.

[40]Ms. Dayan Anderson, President, Mineral Footprint Network

[41]See Appendix III.A for white paper.

Discussion

A participant asked who was responsible for educating the public in this area: Is it the domain of professional societies of trained specialists, such as geologists, mining engineers, metallurgists, and material scientists? Ms. Anderson responded that a meaningful discussion of our mineral footprint was a multidisciplinary problem, which includes not just geologists and other mining-industry professionals, but chemists and people in industries that use mineral commodities. Hence a single professional society would not suffice.

Summary of Key Issues and Themes

- There is limited public awareness of its mineral footprint, analogous to the earliest stages of the environmental movement.
- If efforts to conserve rare materials are to succeed, it is imperative that public awareness be raised.
- As yet, no one has framed a compelling case for husbandry of rare element resources similar to the way that Aldo Leopold's work energized the environmental movement in its early days.

3.2 Considering Resource Availability for Energy Technologies

Dr. Randolph Kirchain[42] spoke at the beginning of the morning discussion session. In his talk titled, "Considering Resource Availability for Energy Technologies[43]," Dr. Kirchain discussed briefly possible irreversible negative consequences of transient shortage events on energy technologies and the beneficial role recycling can play in mitigating such consequences by reducing the impacts of scarcity.

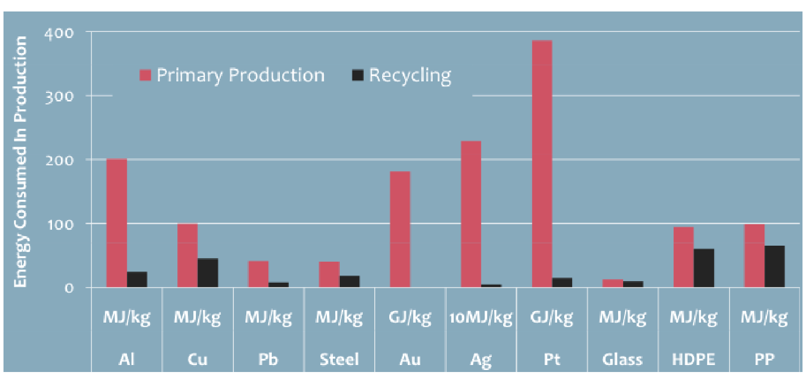
Epitome

Dr. Kirchain began his presentation with MSL's perspective on resource availability: In general they accept standard economic theory, which posits that market mechanisms resolve most issues with scarcity through the supply-demand dynamics and substitution. However, they believe this does not solve all problems, and market imperfections are the focus of his and his colleagues' research.

Dr. Kirchain agreed with Dr. Eaglesham that scarcity arises when the cost of extraction exceeds the market value of an element, and not when it runs out. On account of this, scarcity can cause problems for novel technologies, and it might be in the public interest to intervene. His analysis rested on two key points: incumbency issues and the effect of transient events. *Incumbancy* refers to the phenomenon that once a technology has been adopted, the capital investment, as well as the knowledge of and trust in the technology, including certification procedures, make it difficult to substitute with another technology. Nevertheless, transient events such as shortages and significant price spikes can force substitution of materials and technology. Once a substitution has occurred, the mechanisms of incumbency dictate that even after the transient event has passed, the situation does not revert to its previous state. Thus the change caused by a transient event may become irreversible. Hence, materials technology development is path dependent.

To support these points Dr. Kirchain used the example of Co production in Zaire in the 1970s. At the time, Zaire contained ~40% of the world's Co resources. In 1977, a rebellion in Zaire led to supply constraints on Co and to price speculation. As a result, several irreversible changes occurred. Recycling, stockpiling, technology development to increase process efficiency, and substitution, especially as NdFeB replaced SmCo in permanent magnets, all reduced the demand of Co. Thus, a temporary, short-term event had a long-term effect.

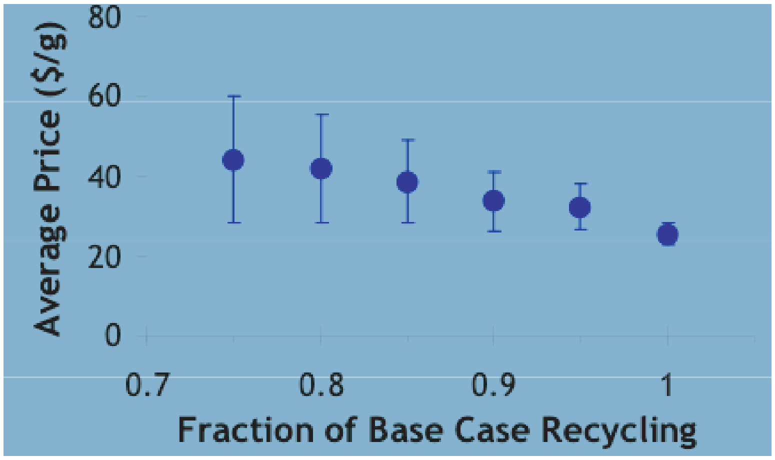
Figure 3.1: The energy savings opportunities in the procurement for metals is shown in this figure. This benefit is large for Al, Au, Ag, and Pt. But even for Cu, and steel, the energy cost is reduced by a factor of 2 when it is obtained from recycling.



[42]Dr. Randolph Kirchain, Materials Systems Laboratory (MSL), MIT

[43]See Appendix II.B.

Figure 3.2: The positive effects of recycling of Pt on its price are shown in this figure. As the fraction of recycled Pt in the market is reduced in this simulation, the price, and associated volatility increases.



Next, Dr. Kirchain described four important benefits of expanded recycling (*secondary production*). The first and most obvious benefit of recycling is a reduction of primary resource depletion. The second is a reduction in energy consumption in production of the metal, which is illustrated for a variety of mineral commodities in Figure 3.1. Stabilization of market dynamics is the third benefit of high levels of recycling. Dr. Kirchain illustrated this benefit by sharing the results of a modeling exercise for Pt, in which product demand, and primary and secondary supplies, are simulated via their price and cross-elasticities. As the fraction of recycled Pt available in the market is reduced, the average price per gram, and the price volatility increase (Figure 3.2). The fourth benefit is that recycling helps diversify institutional and national strategic risk, because primary and secondary supply, in general, do not occur in the same place.

Dr. Kirchain went on to discuss the barriers to implementing and expanding recycling. These include technological, socioeconomic, and policy barriers. The important socioeconomic barriers are low consumer participation, market resistance due to perceptions that recycled metals are of inferior quality, and high transaction costs arising from source-sink dislocation. An example of the latter would be dislocations that arise because a product is produced in China but is consumed in the US, which may not have requisite infrastructure to process and recycle the products that have reached the end of their life. He stressed that these barriers must be overcome if recycling is to be increased.

Dr. Kirchain concluded with some remarks on the importance of transparent information to improve modeling efforts such as those conducted in his group at MSL. These efforts can help identify unintended consequences of policy interventions.

Discussion

A participant suggested that events need not always be caused by the rational explanation we attribute to them. He illustrated this point by noting that the switch away from Co magnets in the auto industry was not driven by the price spike, but rather by a design requirement to build thinner doors, as part of an effort to reduce car size without changing the interior volume. Another example is the recycling of Pt that was instigated by lawsuits against General Motors in Europe for pollution. Pt was used in catalytic converters that also contained Pb. When the $PbSO_4$ clogged the converters, they were disposed in the trash. The Pb then leached into aquifers and polluted the water supply. Thus they were forced to find an alternative solution for the disposal of these catalytic converters, which resulted in Pt recycling. These lawsuits, and not a desire to stabilize the price of Pt, are the real reason for high levels of Pt recycling.

It was also noted that perceived shortages may drive price volatilities when no shortage exists in practice. For example, during 1978, the year in which rebellion occurred in Zaire, more Co was produced than in the preceding year.

After this point, the discussion broadened to all the morning presentations, which is covered in Section 1.4.

Summary of Key Issues and Themes

- Market forces can resolve most scarcity issues.
- However, transient events, such as scarcity, can cause lasting changes in the trajectory of materials technology development.
- Recycling has many potential benefits, among which are 1) ameliorating resource depletion; 2) reducing energy consumption in material production; 3) stabilization of markets; and 4) diversification of risk since primary and secondary sources are rarely identical.
- There are serious socioeconomic as well as technical barriers to increasing recycling.

3.3 Advantage Canada: Materials-Related Policies

Canada is a country with abundant natural resources, and is an important trade partner for the US. It has a well-established regulatory and policy infrastructure to manage its resources. During the session on "Materials Policies of Other Nations," in which the keynote speaker was Dr. Jung-Chan Bae, Dr. Leonard Surges[44] delivered a presentation that highlighted key components of Canadian government policies. His presentation was titled, "Advantage Canada: Materials-Related Policies[45]."

Epitome

Dr. Surges's key message was that Canada not only is an important supplier of minerals, but also has significant influence and presence around the world. Canada provides access to resources and markets, especially in North America. It has encouraged investments and partnerships from foreign sources, and both its imports and exports are large as a proportion of its Gross Domestic Product (GDP). He said that Canada looks forward to the opportunity for collaboration via the Clean Energy Dialogue with the US. This integration into the international market means that they do not consider isolation and self-sufficiency to be a means to security.

Dr. Surges pointed out that Canada, along with Australia, is anomalous among the developed countries, in that resource extraction is a significant source of GDP. This is a capital-intensive sector, and the Canadian government has always welcomed foreign investment. In the past, the source of foreign investments was Britain and the US, then Japan and Korea, and now increasingly, China.

Canada has a large and diverse landmass. It is a leading minerals and energy producer and exporter, and has evolved quite a different approach to mining than the US. In Canada, unlike much of the US (with the exception of public lands managed by the federal and some state governments), mineral rights are owned by the government, and are managed by them strategically. However, they believe that the government is not the appropriate entity to develop these resources; rather its role is to support investments and development by private investors. The government facilitates this by providing relevant knowledge and infrastructure. Dr. Surges elaborated that federal and provincial geological surveys generate knowledge used to identify exploration targets, and make this information available to industry. Canada has world-class public geological surveys, and is a leader in geoinformatics. Additionally, data and assessment reports from industry are made accessible to the public. Mining claims are open to everyone, and can be staked online, but are subject to work requirements. The government also builds relevant infrastructure, such as electricity transmission lines and roads, in areas new to development. An example is federal and provincial government investment in electrical transmission lines in British Columbia to facilitate mine development. There are also various tax incentives that help small investors.

Dr. Surges stressed that Canadian policies are generally not material specific, and support Canada's position as a global leader in sustainable mineral resource development. It provides an environment conducive to foreign investments with favorable tax rates. And Canada's influence extends to most countries and regions with mineral potential, because Canada provides the business environment, largely through the Toronto Stock Exchange, for the investment in worldwide exploration for mineral resources. The Prospectors and Developers Association (PDAC) of Canada further provides a forum for investors interested in mineral resources in both Canada and other parts of the world.

[44]Senior Advisor to the Assistant Deputy Minister, Minerals and Metals Sector, Natural Resources Canada

[45]See Appendix II.C.

Dr. Surges noted that smaller companies are advancing projects that could eventually increase rare-metal reserves and production in Canada and abroad. Lithium, REE, and other rare metals are attracting growing interest. For example, in 2008, 11 operators spent $16 million at 16 REE projects in Canada. But new mines are only the first step in ensuring availability of value-added materials components, since what is extracted must be processed. However, Canada has expertise in rare-metal processing, distribution, and recycling.

Discussion

During the discussion, one participant asked Dr. Surges to describe the Canadian National Instrument 43-101 rules. Dr. Surges clarified that rules describe the standards for disclosure to investors in mineral properties traded on the Canadian stock exchanges, including requirements for classifying a resource as a reserve. They require that the resource must have been the subject of geologic research, must be technically feasible to mine and process, must have been demonstrated to be developable, and have been the subject of a bankable feasibility study[46].

Dr. Surges was asked if the Canadian government has units similar to the USGS Minerals Information Team. He responded that the equivalent unit was within Natural Resources Canada. Their data was comprehensive and up to date for production information, reserves, and descriptions of deposit-appraisal activities in Canada. Companies are required to provide data on exploration, production, and reserves to the government[47]. Their reserve numbers are conservative because of stringent reporting conditions.

Summary of Key Issues and Themes

- Canada is an important supplier of minerals, and has significant influence and presence around the world.
- Canada's model for mineral development provides a useful contrast to the US model. In particular, mineral rights in Canada are owned by the Crown.
- The government's role is to gather and make available relevant information, provide relevant infrastructure for resource development, and provide an environment conducive to investments.

[46]A bankable feasibility study is a document demonstrating technical feasibility that a company would take to a bank when attempting to finance the project.

[47]The US does not require such turnover of data and information. See NRC Critical Minerals Study (2008), which discusses the difference between "primary" and "other" statistical agencies in the US. Primary statistical agencies have legal authority to require that companies respond to requests for information. USGS MIT is not a primary agency.

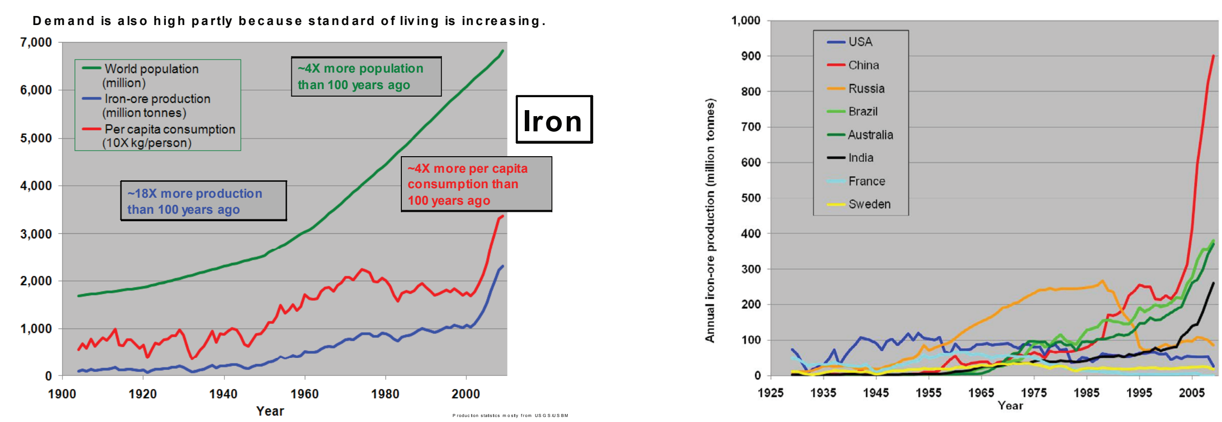
CHAPTER 4 – Summary and Concluding Remarks

The workshop was brought to an end with concluding remarks from conference co-chair Dr. Jonathan Price, State Geologist and Director, Nevada Bureau of Mines and Geology. The diverse set of topics in the evening and morning programs shared themes and issues associated with geology and mineralogy, new uses for by-product elements, effective and ineffective government intervention, resource constraints, and concentration of production in China. He reviewed and summarized the key points in the white papers and presentations of the speakers, and the issues brought forward in the discussion sessions.

Epitome

Dr. Price began his remarks by bringing attention to the increase in metal production and consumption globally over the last century. Over the last two decades, China has surpassed all other countries in the production of iron ore. Trends are shown in Figure 4.1.

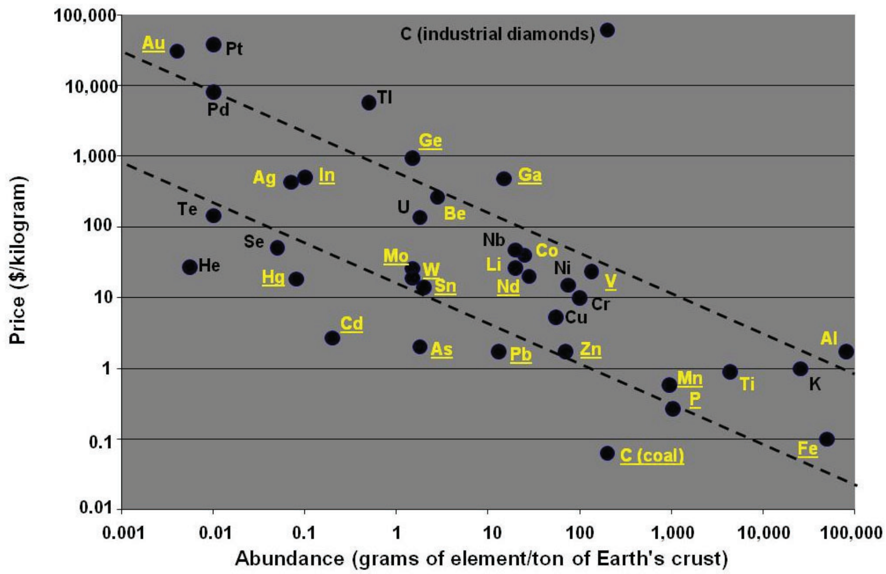
Figure 4.1: The left panel shows that during the 20th century, both the world population and the per capita consumption of iron have increased more than four-fold. This translates to a production increase by 18 times for iron. The right panel shows the production by the major producing countries. Over the last two decades Chinese production has surpassed all other countries.



Dr. Price introduced the summary using Figure 4.2, which is a scatter plot of unit price vs. crustal abundance. At a high level, higher crustal abundance and lower unit price are positively related. The REEs are located in the center of the figure. However, there is a wide spread in the scatter due to a variety of possible reasons, which need more data for a better understanding. Aluminum (Al) is more expensive than Fe, even though they have similar crustal abundances, because of the high price of electricity needed to break Al-O bonds in extracting Al from its ores compared to the relatively low price of coal used to reduce Fe ore in making steel. The higher cost for processing Al probably makes its by-product Ga also more expensive than a median trend would suggest. Cd has an abnormally low price compared to its crustal abundance most likely because it is an undesirable substitutional impurity in Zn and must be removed in Zn processing.

China's dominance can be seen by noting that among the 37 elements shown in Figure 4.2, it is among the top three producers for all elements shown in yellow (24 elements), and the biggest producer for those underlined (18 elements). In contrast, the US is the top producers of only beryllium (Be) and He and among the top three of 9, while Canada is the top producer of U and potassium (K) and among the top three for 6 elements only. Appendix IV.A contains a table of leading producers for key elements, prepared by Dr. Price.

Figure 4.2: The price vs. the crustal abundance of various metals and ECEs is shown in this figure on a log-log scatter plot[48]. Elements below the bottom dotted line have low price compared to their crustal abundance and vice versa. China is among the top three producers for the elements shown in yellow and the leading producer for the underlined ones.



Dr. Price then brought attention to the various issues raised and points made by the keynote and supplementary speakers in their white papers or presentations:

Rare Earths and Related Issues

The Nature of Economic REE and Y Minerals on a World Level, by Dr. Anthony Mariano

- Currently production of REEs is dominated by China. However, globally there are deposits with sufficient resources to meet future needs. These deposits have the potential to change the current situation, if and when they come online.
- Different deposits have their own, often unique mineralogical complexity, and need economic extraction technology.

Cadmium/Tellurium and Related Issues

Tellurium for Photovoltaics, by Dr. David Eaglesham

- In the short term, there are many sources of Te supply uncertainty that do not depend on the reserve volume. These effects are mediated via different supply elasticities.
- In the long term, there is no serious resource limit.
- Price volatility presents a significant challenge to PV manufacturers. This is a potential area for policy intervention.

[48] Prices are mostly averages for the year 2009 from US Geological Survey (2010); U price from Cameco (24 December 2009, http://www.comeco.com); Li price from Davis (2009); Nd price from Metal Pages (24 December 2009, http://www.metal-pages.com/); Nb price from MetalPrices.com (24 December 2009, http://metalprices.com/), using the 31 December 2007 quote; crustal abundances mostly from Mason (1966); He abundance from Web Elements (24 December 2009, http://www.webelements.com/helium/).

Helium and Related Issues

Selling the Nation's Helium Reserve, by Dr. James Lancaster

- The federal He reserve is large. However, new potential sources in Wyoming (1.5 Bcf reserves) and by-product production in liquefied natural gas are significant potential resources.

- He has diverse applications and uses, and its market is changing.

- In a multidisciplinary workshop such as this one, the description of timescales is relative. The NRC study uses 15 years a long-term time frame, while in the mining business 10 to 15 years are typically needed to bring a mine online after the geologic work of delineating the resource is completed.

- The NRC study has recommended the creation of a standing committee to study the market, so that we are not caught unawares again.

- There is a need for information gathering and availability.

Substitutional Research in Physics, Chemistry, and Materials Science

Mined Resource Constraints on Solar Energy and Battery Storage Potential, by Dr. Cyrus Wadia

- Considering pyrite (FeS_2) as a potential useful PV technology requires attention to potential adverse environmental impacts, recognizing that oxidation of pyrite is the cause of acid mine drainage in Appalachia and elsewhere.

- The future technology mix for PVs may look different from the current landscape of CdTe and CIGS TFPV and Si-based technologies.

- The near-term application for battery storage will be in electric vehicles. This limits the choice of batteries to lightweight Li-ion batteries. The use of batteries for grid-level storage of electricity will be much further out.

Tracking Critical Elements in the US

Supply and Demand for Selected Energy Related Mineral Commodities, by Mr. Scott Sibley

- The current technology that is primarily used for Cu extraction in the US is solvent extraction/ electrowinning. This does not allow for extracting Te, which ends up in tailings. Extracting Te from these tailings is a potential metallurgical research area.

- There is geologic and geographic diversity in the potential sources of minerals.

- There are sufficient reserves available for most elements of interest for this workshop when compared to annual production and consumption.

- Limited mine production and plant capacity can lead to short-term supply shortfalls.

- Recycling has the potential to be a significant source of materials.

Materials Policies of Other Nations

Strategies and Perspectives for Securing Rare Metals in Korea, by Dr. Jung-Chan Bae

- Korea is focusing on 11 strategic elements needed for their industries. Their initiative includes focus on different aspects of the supply chain, such as resource exploration abroad and R&D for refining, smelting, processing, materialization, and recycling.

- Korea's program for strategic elements contains recycling or urban mining (extracting elements from municipal and industrial waste) as an important component of their strategy.

- Electronic products that have reached their end of life have significant quantities of certain elements. An example of this is Au. A tonne of Au ore typically contains 5 grams of Au; a tonne of discarded mobile phones contains 400 grams of Au; a tonne of discarded personal computers contains 52 grams of Au; and a tonne of discarded home appliances contains 20 grams of Au. Furthermore, a tonne of discarded mobile phones also contains 100 kilograms of Cu, 3 kilograms of silver (Ag), 20 grams of Pd, and other metals that could be recycled[49].

Supplementary Presentations

A Communications and Outreach Perspective, by Dayan Anderson

- Attention needs to be paid to how the topics under discussion at this workshop are conveyed to the general public. Their understanding and support are important.

Considering Resource Availability for Energy Technologies, by Randy Kirchain

- Recycling on a significant scale helps stabilize prices. It also reduces strategic risk because recycling will take place within the country of consumption.

Advantage Canada: Materials-Related Policies, by Leonard Surges

- Canada has a system in place to store exploration and resource assessment data. These data and assessment reports from industry are accessible to the public. The US has a huge vacuum in this area, where company data on federal lands is not stored and made openly accessible. Similarly the Canadian claim-staking process is superior to the US procedures.

- The PDAC annual meetings, where 17,000 miners gather to promote various properties around the world, provide a venture capital environment for mineral exploration.

In conclusion, there is interplay between the dynamics and flux of technology, policy, and their relative timing. The materials demanded today by technology can change — the elements that have been the focus of this workshop have gained their importance only in the last decade. On the other hand, policies that we create and implement today have implications 10 to 15 years down the line.

[49]This point was made in Dr. Jung-Chan Bae's white paper submitted prior to the workshop, which has not been included in the appendices.

APPENDICES

The speakers in this workshop all submitted presentations while some submitted additional white papers. In the interest of space, where there was the option to choose, we have included either the presentation or the white paper depending on our judgment of added value. There are two exceptions, Dr. Anthony Mariano, and Dr. David Eaglesham. For Dr. Mariano, we have included both the white paper and the presentation because of the complexity of the subject and the added value of viewing both together. The material provided by Dr. Eaglesham was not for public release, and has not been included in the appendices. The appendices also contain formal responses; one response is to Dr. James Lancaster's and two responses are to Mr. Scott Sibley's presentation; and a table for the three leading producers of selected elements prepared by Dr. Jon Price.

White Paper, Anthony Mariano,
The Nature of Economic REE and Y Minerals on a World Level

The Nature of Economic REE anbd Y Minerals on a World Level

Anthony N. Mariano

Introduction

Although the term “rare earths” is considered to be a misnomer to many, a comparison of their crustal abundance (Table 1) with other better known rare elements shows that at least some are indeed relatively rare. None are as rare as Au but their extraction as pure elements requires a higher technology than the winning of Au. The rare earth elements (REE) are conveniently divided into two sub-groups: those of lower atomic number and masses being referred to as the light rare earth elements (LREE), and the higher atomic number and masses being referred to as the heavy rare earth elements (HREE). The distinction for the division between the LREE and HREE varies amongst investigators, but generally falls close to the midpoint.

The elusiveness of the rare earths is further magnified by their dispersion as substitutional impurities in many rock-forming minerals. Only a few minerals contain major quantities of REE, and are sufficiently concentrated to constitute economic ore deposits. Some of the major REE and Y bearing minerals are listed in Table 2. Of these minerals bastnaesite and monazite account for virtually all of the historical world production.

Source Localities for REE and Y Minerals

Most independent REE minerals and accessory minerals which concentrate REE are found in pegmatites or highly-alkaline rocks, indicating that the bulk of the REE tend to become concentrated in the final stages of magmatic differentiation.

The greatest concentration of rare earths occurs in a special type of igneous rocks known as carbonatites. These rocks are composed predominantly of calcite or dolomite. They are associated with strongly alkalic silicate rock units and they originate below the crust, in the earth's mantle. Examples include Mountain Pass, California; Mt. Weld, Western Australia; and Itapirapuá, São Paulo state, Brazil.

In less concentration but of more widespread distribution are the heavy mineral deposits in beach sand, and river placers found in every continent.

Another source of rare earth concentration is in alkali granite and quartz-syenite complexes where HREE dominate. Examples are Strange Lake, Quebec-Labrador and Thor Lake, Northwest Territories, Canada.

The Mountain Pass deposit in California is a unique carbonatite occurrence where bastnaesite of primary igneous crystallization is mined in an open pit operation. Reserves at the end of 1986 were estimated at 40 million tons of 7.67% REO.

Hydrothermal REE mineralization associated with carbonatites is more common. Examples include the Karonga, Burundi high-grade bastnaesite-monazite veins that have been intermittently mined by hand labor methods, and the colossal Bayan Obo deposit of Inner Mongolia, China. Another example of potential high-grade REE mineralization of hydrothermal origin is the Wigu Hill carbonatite of southern Tanzania. Ore minerals at Wigu include bastnaesite, monazite, parisite and synchysite. Some hydrothermal occurrences have interesting potential but poor logistics. An example is the Adiounedj carbonatite of the central Sahara in Mali where synchysite is co-crystallized with fluorite and quartz. Remoteness in this area precludes economic considerations.

Monazite deposits in beach sands on a world level offer sustained sources of REE but they are usually byproducts of other heavy mineral mining and often constitute less than 2% of the ore mined. A high-grade hardrock REE deposit is a better target.

REE Distribution in Minerals

A major hurdle for current growth in the sales and use of permanent magnets is the price of the refined REE products. One reason given for the high costs is the presence of major amounts of La and Ce in the initial mineral sources and the fact that in order to extract Nd, Sm, and Dy, very large quantities of La and Ce compounds are produced and must be stockpiled.

In the theoretical formula bastnaesite has a higher ReO content than monazite by 5%. In addition most placer monazites contain Ca and Th at the expense of REE which further reduced their REO content. Both minerals are most often LREE dominant with bastnaesite being more selective than monazite.

The summation of La_2O_3+CeO_2+Pr_6O_{11} (Table 3) represents 88% and 75 percent of the total REO for Mt. Pass bastnaesite and for Australia monazite respectively.

A convenient way for data presentation of the REE distribution in minerals can be made by plotting the ratio of each REE in a mineral to the corresponding value in chondritic meteorites (on a logarithmic scale) as a function of ionic radii or atomic number. This normalization to chondrite values removes the element-to-element irregularity and exposes small relative abundance variations for neighboring REE that result from natural processes. In Table 3 the composition of the main REE and Y ores are tabulated. Columns 2 and 4 are two different analyses for Australian monazite. A chondrite normalized plot for columns 3 and 4 is given in Figure 1. Both analyses show relatively smooth curves with exception for the typical negative Eu anomaly. The respective LREE and HREE dominance for monazite and xenotime are clearly demonstrated.

Although the monazite and bastnaesite structures are mainly LREE selective, variations in the REE distribution can be encountered, especially in crystallization from hydrothermal and weathering environments. Examples where Nd is the major REE in monazite include an alpine vein occurrence in Italy (Figure 2) and fissure veins in bauxite from Greece. These and other examples demonstrate that major REE-bearing minerals that are normally LREE selective may also show intermediate REE enrichment.

New Potential Sources

The ideal target for REE minerals would be a deposit containing economic grade and tonnage preferably enriched in the mid atomic number REE and including good values of yttrium.

The greatest repository for rare earths in the world occur in carbonatite complexes where substitutional impurities of REE in rock forming minerals including calcite, dolomite and apatite have been leached out by hydrothermal or weathering processes and recrystallized and concentrated as secondary major REE-bearing minerals. Notice in the previous sentence that the source for the REE was not from primary independent REE minerals. The secondary minerals may include monazite, rhapdophane, parisite, synchysite, ancylite, florencite, xenotime, churchite, britholite and crandallite group minerals. Large quantities of weathering product REE minerals can be produced in carbonatites from tropical climates with moderate to heavy rainfall and where interior drainage in a basin - type topography allows the entrapment of decalcified carbonatite residuum. Examples include Araxá, and Catalão I, Brazil; Cerro Impacto, Venezuela; Mrima, Kenya and Mt. Weld, Australia. Lateritic weathering in these environments can extend to depths of 300 meters. A mid-atomic number enrichment is usually present in REE minerals from these environments (Figure 3) and in several cases including Mt. Weld, Australia, Y is selectively fractionated producing xenotime and the hydrous yttrium phosphate churchite.

Several of these supergene REE deposits exist in the Amazon area of South America where logistics and environmental considerations are a hindrance to development for mining. Others occur in more favorable areas however the secondary minerals are most often very fine-grained and inextricably associated with ferric iron oxides and other gangue minerals. Economic beneficiation of this type of mineralization will require innovations in mineral processing. In several mines operated for other mineral commodities the supergene REE minerals end up in tailings ponds.

The Xun Wu deposit from Jiangxi Province in China is reported to be producing rare earths at low prices from very low grade ores (o.n wt.%). According to Industrial Minerals (Nov., 1988) REE are absorbed on the surface of alumino silicate minerals including kaolin. The ore is also reported to be Ce and Y-poor but relatively Eu-rich. A chondrite-normalized plot for the Jiangxi ore at 0.1 wt.% ∑REE of Figure 4 shows a very strong Ce and Eu negative anomaly while the remaining REE show the normal smooth curve with an LREE dominant trend. Analyses performed on one Jiangxi concentrate (unpublished data, A.N. Mariano) showed microcrystalline bastnaesite and cerianite attached to kaolin and associated with K feldspar, quartz, anatase, biotite, magnetite, and zircon. Energy dispersive x-ray spectra for the bastnaesite crystals attached to kaolin and magnetite showed L series emission energies for La and Nd but the Ce L lines were absent.

The ion-adsorption type lanthanide deposits are hosted by laterites that occur throughout South China, especially in the Provinces of Jiangxi, Guangdong, Hunan and Fujian where they have been commercially developed. Over 100 deposits are known. The deposits are low-grade, 0.03 to 0.2 total REE and Y; low tonnage, 3,000 to 12,000 ton reserves; and are low-cost producers. Production costs are low because (1) the deposits are hand mined in shallow open pits by cheap labor, and (2) ore processing is relatively simple involving deabsorbtion with a weak acid followed by the production of lanthanide oxide through the calcining of lanthanide oxalate precipitated from the acid extract. Low radiation levels of these deposits decrease some environmental concerns associated with the mining, but the disruption of large quantities of laterite has a major deleterious affect on the environment.

At this time the South China deposits constitute the major world source for Y and HREE. These deposits account for ≈ 30% of world REE production

Ion Adsorbed Clays Mining Procedure

1) The lateritic ore is a whitish colored regolith soil that is mined from nearby hills. Surface areas have been exposed by removal of trees and vegetation. The ore extraction may be selective along bands that are lighter than adjacent soil. This could be fracture dependant where lateritic weathering has been more advanced. 2) Somewhere nearby pits are dug and plastic linings placed in the pit bottoms to prevent escape of fluids. Pits are filled with water and ore. The pit material is then exposed to leaching with H_2SO_4 or ammonium sulfate.
3) The fluids are later siphoned downhill into another concrete pool.
4) These fluids are exposed to oxalic acid, and REE oxalates are then precipitated.
5) The precipitate is collected into a calcining kiln and fired up.
6) The end product is stored into bags.

Some other mineral deposits with large tonnage of attractive REE values include Olympic Dam and the Brockman deposit of Australia, and Thor Lake and Strange Lake of Canada. These are all hardrock deposits where REE minerals would be byproducts of other commodities. The grain size and nature of associated minerals introduce major problems in beneficiation. The Strange Lake deposit is remotely situated near the Arctic Circle. Mineral commodities include Zr, Be, Y, N, and Ta. The deposit is strongly HREE enriched from a late episode of Ca-metasomatism producing kainosite and several other unidentified and new yttrium silicate minerals.

REE and Y as By-products of Other Mining Activity/Impact on Price and Availability

Most monazite mining in beach sands and placers is produced as a byproduct of some other mining activity including ilmenite, cassiterite, rutile and zircon. Prices and availability can be subject to changes in mining activity for titanium. Currently the demand for titanium is high.

Since 1980 there has been growing activity in exploration and evaluation of eudialyte mineralization in peralkaline granite and nepheline syenite environments particularly in several localities in North America and Greenland. The mineral eudialyte is a sodium calcium zirconosilicate [Na_4 $(Ca,REE,Fe)_2ZrSi_6O_{17}(OH,CL)_2$]. In some occurrences it is found to contain an average of 2 wt.% Y and for one occurrence in Greenland Y values are reported as high as 4 wt.%. In addition to Y eudialyte also contains other REE. Chondrite-normalized REE plots for eudialytes show relative enrichment for mid-atomic number elements including Nd, Sm and Dy, and a negative anomaly for Eu. The mineral often averages 20% of the contained rock unit, and in Greenland and the Kola Peninsula of USSR it can be a major rock-forming mineral exceeding 50% in some exotic alkaline rocks (Kakortokites and Lujavrites). Eudialyte is easily concentrated and readily acid soluble yielding high grade ZrO_2 and Y_2O_3 products. If this type of ZrO_2 is attractive to glass and ceramic producers the mining of eudialyte can have a strong impact on price and availability of yttrium.

In the Elliot Lake area of Ontario, Canada yttrium was a byproduct of uranium mining where it was extracted from the mineral uraninite (UO_2). With changing market conditions yttrium recovery at Elliot Lake, at times has been uneconomical and currently yttrium from Jiangxi is reported to be a less expensive source.

The mineral apatite from carbonatites and alkaline igneous rocks is almost invariably anomalous in substitutional REE. For example some apatite from the Bond Zone at Oka, Quebec averages greater than 7 wt.% REE. Apatite from some alkali syenites contain >19 wt.% REO. In general however, carbonatite apatites rarely exceed 2 wt.% REE, and at present REE are not a byproduct of phosphate mining in carbonatites. In contrast marine phosphorites contain between 100 and 1500 ppm REO.

By the next decade the increasing world demand for phosphates will not be met by production of U.S. marine phosphate reserves (currently the world's largest producer) because of incipient land use restrictions, permitting restrictions for phosphate mining and processing, increasing environmental regulations, and higher production costs. Therefore the future outlook is for a world increase in phosphate mining of carbonatite apatite. In the initial stages of designing mining and beneficiation schemes for igneous apatite, consideration should be made for the feasibility of extracting byproduct rare earths.

Another potential source of byproduct rare earths can come from the mining of anatase in the residual laterite regoliths that overlay the carbonatites of Tapira, Salitre I, II and Serra Negra of Minas Gerais. Catalão I of Goiás in Brazil. In these carbonatite complexes vast tonnages of TiO_2 occur as anatase that is a decalcification weathering product of perovskite from pyroxenite units. The anatase concentrates average about 2.5% REE consisting of the typical supergene minerals including monazite, florencite, rhapdophane, bastnaesite and cerianite. As deleterious components in the anatase concentrates, mining of these ores will necessitate the extraction of the REE minerals. It is conceivable that the carbonatites of Brazil with REE sources in laterites from the niobium mines, igneous apatites, and anatase deposits can have a profound affect on price and availability.

Table 1 Crustal Abundance of REE Compared with Some Other Elements* (ppm)

La	58	Cr	670
Ce	74	Co	12
Pr	11	Ni	37
Nd	41	Cu	32
Sm	7.4	Zn	63
Eu	1.6	Ga	18
Gd	6.6	Ge	1.3
Tb	1.1	As	1.7
Dy	6.8	Ag	0.06
Ho	1.5	Au	0.002
Er	3.9	Hg	0.03
Tm	0.59		
Yb	3.7	Y	38
Lu	1.0		

* From K.K. Turekian in *Encyclopedia of Science and Technology*, Second Edition, McGraw-Hill, 1971.

Table 2 Major REE & Y Bearing Minerals*

Mineral	Formula	Theoretical REO%
Bastnaesite	$(REE)(CO_3)F$	74.81
Monazite	$(REE)PO_4$	69.73
Parisite	$Ca(REE)_2(CO_3)_3F_2$	60.89
Synchysite	$Ca(REE)(CO_3)_2F$	52.64
Ancylite	$Sr(REE)(CO_3)_2(OH)\cdot H_2O$	47.98
Xenotime	YPO_4	69.73
Florencite	$(REE)Al_3(PO_4)_2(OH)_6$	31.99
Rhapdophane	$(REE)PO_4\cdot H_2O$	64.83
Britholite	$(REE,Ca)_5(SiO_4,PO_4)_3(OH,F)$	≈ 60
Kainosite	$Ca_2(Y,REE)_2(Si_4O_{12})CO_3\cdot H_2O$	≈ 38
Allanite	$(REE,Ca,Y)_2(Al,Fe^{3+})_3SiO_4)_4(OH)$	variable (as high as ≈ 27)

* Minerals where REE are major cations, and that are known to, or have the potential of occurring in ore quantities.

Table 3 Major Rare Earth Ore Minerals (Oxide %)

	Bastnaesite Mt. Pass	Monazite Australia	Xenotime Malaysia	Monazite Australia
La_2O_3	26.06	11.55	1.75	13.46
CeO_2	36.81	25.66	4.22	27.20
Pr_6O_{11}	3.02	2.98	0.51	2.98
Nd_2O_3	7.54	10.75	1.83	10.76
Sm_2O_3	0.38	1.61	0.67	1.35
Eu_2O_3	0.07	0.03	0.01	0.04
Gd_2O_3	0.09	0.80	2.50	0.99
Tb_4O_7	0.02	0.08	0.33	0.09
Dy_2O_3	0.01	0.32	3.70	0.30
Ho_2O_3	0.002	0.04	0.92	0.05
Er_2O_3	0.005	0.06	3.14	0.08
Tm_2O_3	0.0007	0.008	0.49	0.008
Yb_2O_3	0.0004	0.02	3.19	0.036
Lu_2O_3				0.004
Y_2O_3	0.04	0.83	30.86	1.17
ThO_2	0.09	5.73	1.26	6.5
$REO+ThO_2$	74.66	61.1	55.4	65
Theoretical REO	74.81	69.73	61.40	69.73

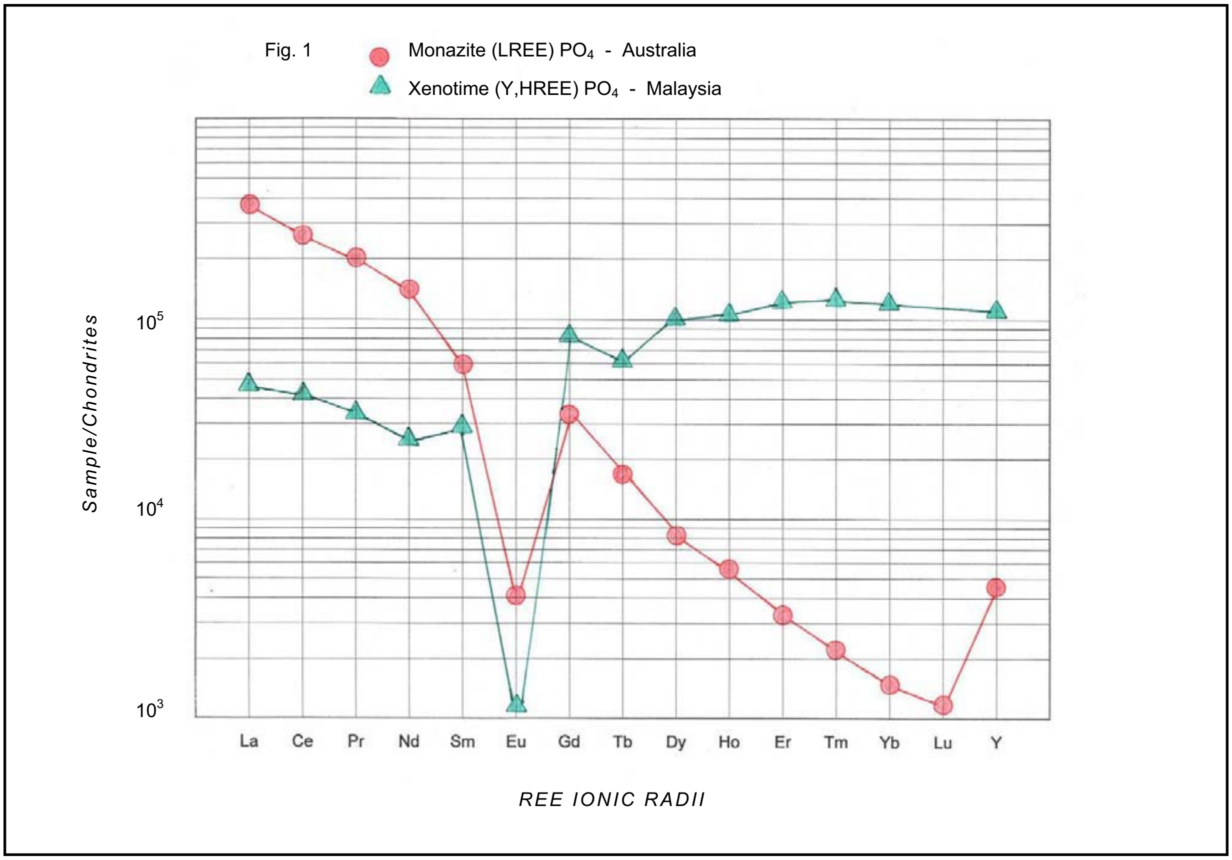


Fig. 1
Monazite (LREE) PO_4 - Australia
Xenotime (Y,HREE) PO_4 - Malaysia
Sample/Chondrites
10^5
10^4
10^3
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Y
REE IONIC RADII

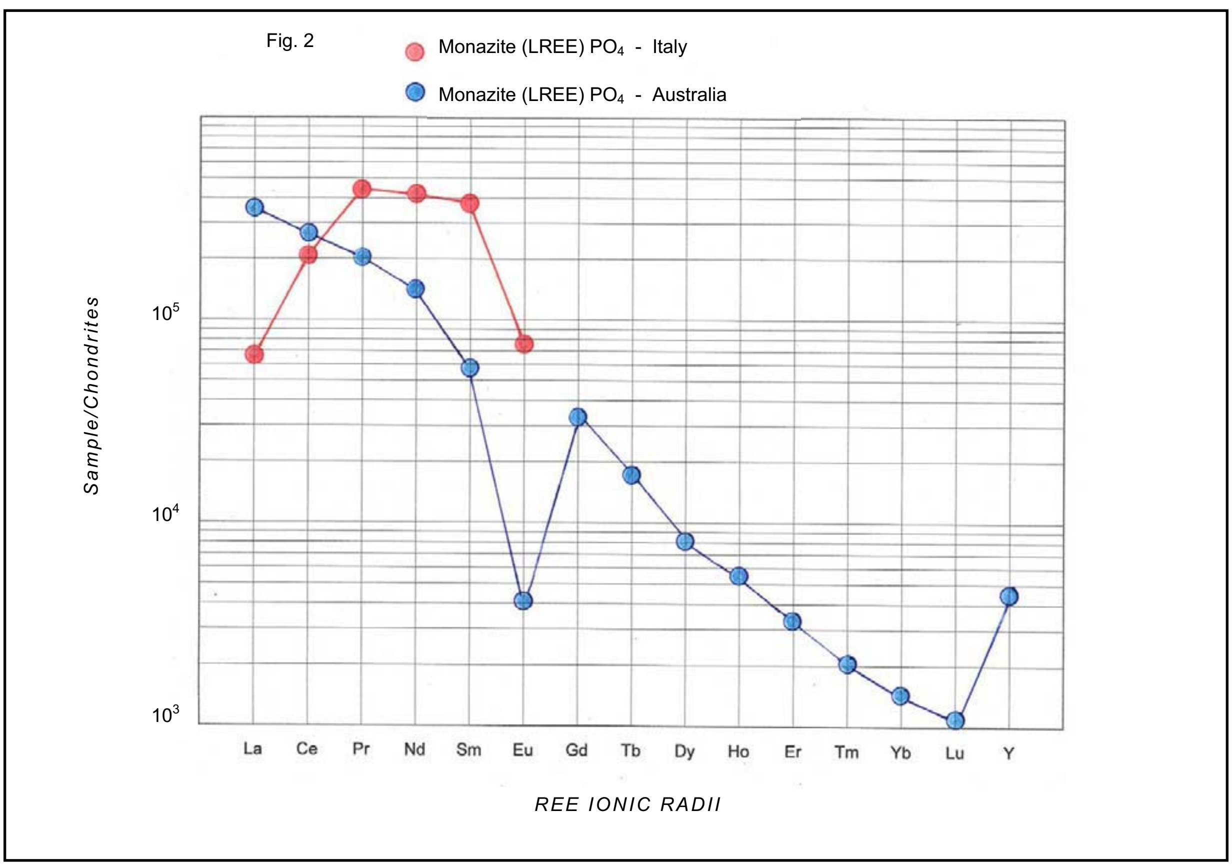


Fig. 2
Monazite (LREE) PO_4 - Italy
Monazite (LREE) PO_4 - Australia
Sample/Chondrites
10^5
10^4
10^3
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Y
REE IONIC RADII

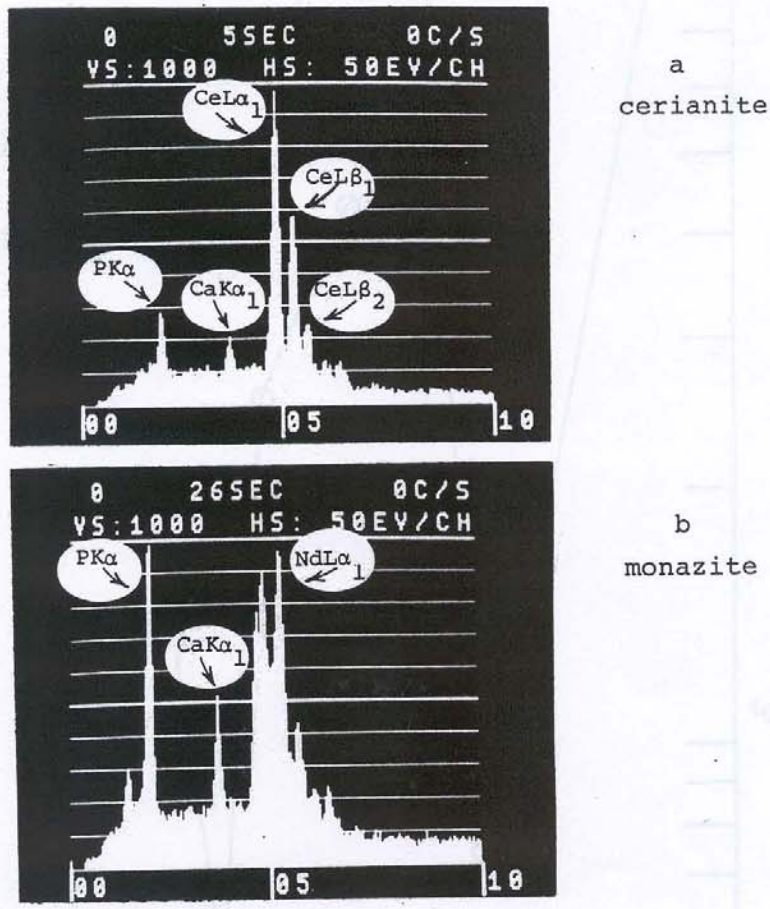


Fig. 3 Energy Dispersive X-Ray Spectra for Supergene (Weathering Product) Monazite and Cerianite (CeO_2) from Carbonatite Laterite.

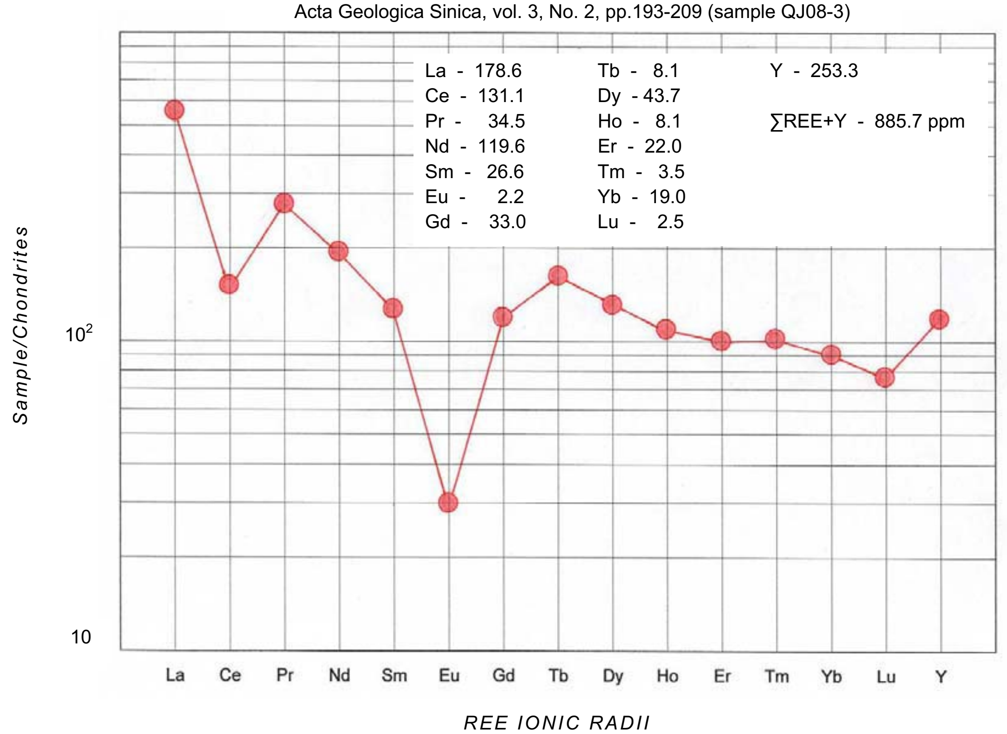
The excellent resolution of the Ce L series lines in (a) establishes that the mineral is predominantly composed of Ce. In (b) there is a distinct positive anomaly for Nd. This type of supergene monazite is strongly enriched in Nd.

The formation of cerianite in these environments is due to the oxidation of Ce^{3+} to Ce^{4+} and its subsequent separation from the other REE.

Fig. 4 Chondrite-Normalized Plot for South China Clay – Jiangxi Province

Wu Chengyu, Huang Dianhao and Guo Zhongxun (1990)

Acta Geologica Sinica, vol. 3, No. 2, pp.193-209 (sample QJ08-3)



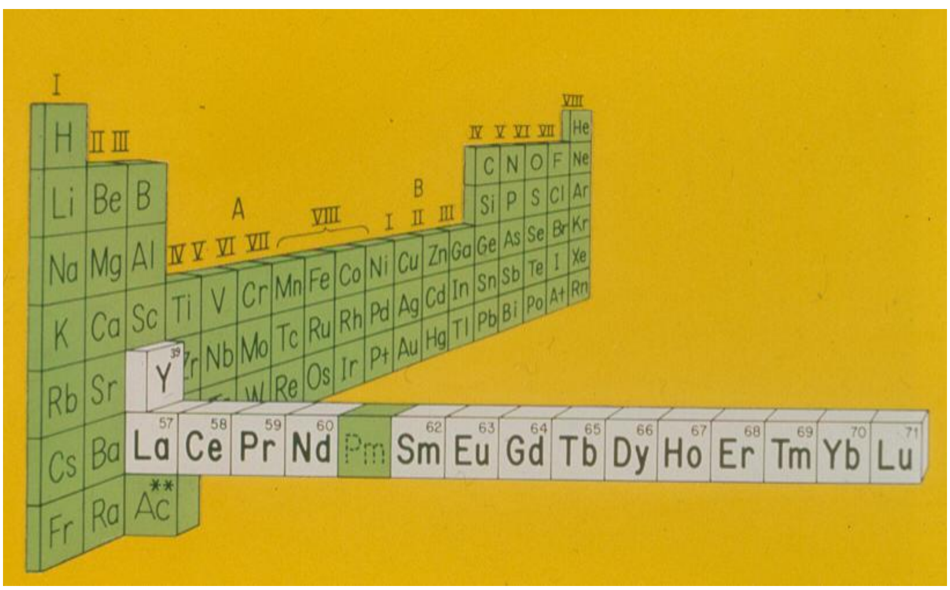
Presentation, Anthony Mariano,
The Nature of Economic REE and Y Minerals on a World Level

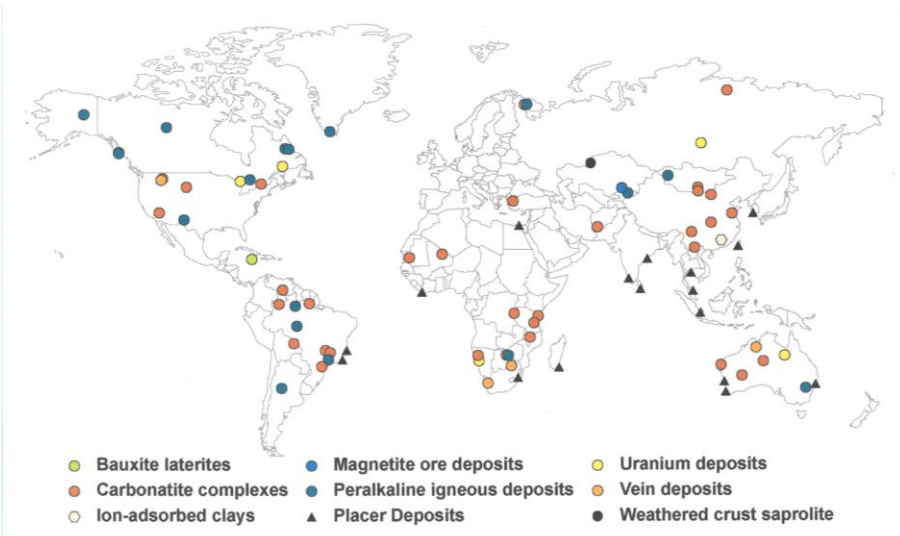
The Nature of Economic REE and Y Minerals on a World Level

Anthony N. Mariano, Consultant, Carlisle, MA

APS – MITEI – MRS Workshop April 29, 2010

REE and Y in the Periodic Chart





Major Rare Earth Sources

Mineral	Composition	Occurrence
Bastnäsite (Ce)	(REE) CO_3F	Carbonatites
Monazite (Ce)	(REE) PO_4	Beach Sands, Hydrothermal
Xenotime (Y)	(Y,REE) PO_4	Beach Sands, Hydrothermal
Loparite (Ce)	(REE,Na,Ca) (Ti, Nb,Ta)O_3	Alkaline igneous massif
South China Clays	(Ion-adsorbed REE+Y in Clays)	
Uraninite	(REE and Y — Released as dissolved elements in rafinates from uraninite)	

The Major REE and Y World Resources

Bayan Obo – Inner Mongolia, China	LREE (bastnäsite)	1,460 mt @ 3.9 wt.% REO	Operational
Mianning County - Sichuan, China	“ “	Conservative estimate in 1994 > 5 mt of 3 wt.% REO	“
Weishan Lake – Shandong, China	“ “	Six% of REO production in China In 1992	“
Mountain Pass - CA, USA	“ “	≈ 40 mt 8 wt.% REO	Operation currently suspended
Ion-Adsorbed South China Clays	LREE + HREE in clays	Average mining grades of mineralized laterite ranges between 0.1-0.03 wt.%· ·REE+Y	Major world source of HREE
Lovozero Massif, Kola Peninsula, Russia	LREE (Loparite)		Operation currently suspended

Sporatic and un-sustained small scale production of monazite $(REE)PO_4$ and xenotime $(Y,HREE)PO_4$ are mined from beach sands from India, Malaysia, Indonesia, Thailand, Africa and Australia.

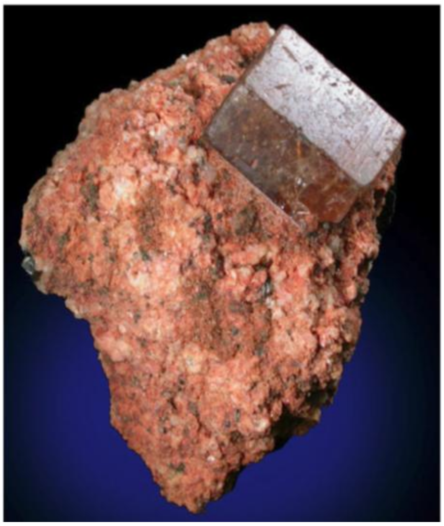
Major Requirements

Assuming a favorable political climate and good logistics, conditions determining the viability of deposits that can compete in the world market are as follows…

1) Mineralogy and favorable lanthanide distribution
2) Grade and tonnage
3) Amenability to mining and mineral processing at low costs, and successful chemical cracking of the individual lanthanides for their isolation
4) Acceptable low values of accompanying thorium, uranium and other deleterious impurities
5) Minimum impact on the environment

Any lower production costs can significantly reduce the grade requirements

Bastnäsite



- Bastnäsite [(REE)(CO_3)F], is the world's most important source of LREE
- Containing 75% rare earth oxides (REOs)
- Bastnäsite from all sources currently mined is LREE – dominant with virtually no contained HREE.

Zheng Jia Liang Zi - Mianning

Bastnäsite REE CO_3F

Major World Source of LREE

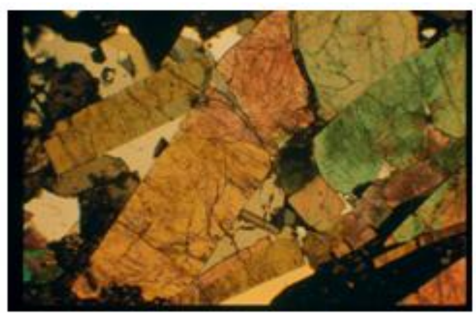
- Bayan Obo – Inner Mongolia, China
- Mianning – Sichuan, China
- Weishan – Shandong, China
- Mountain Pass – CA, USA
- Karonga – Burundi

Potential Sources

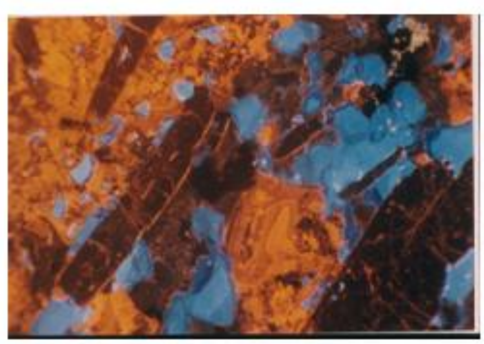
- Dong Pao – North Vietnam
- Wigu Hill – Tanzania
- Kizilcaören – Turkey
- Wicheeda Lake –British Columbia

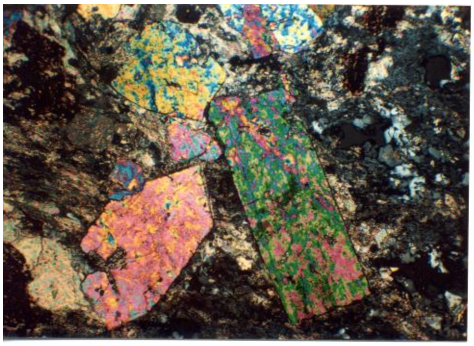
Photos from Camp at Mu Lou Village 1/13/94

XPL Micrograph of
Bastnäsite Carbonatite

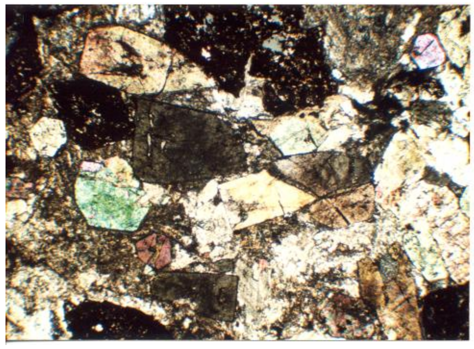


CL Micrograph
Bastnäsite
Fluorite
Calcite





HD - 1.76 mm

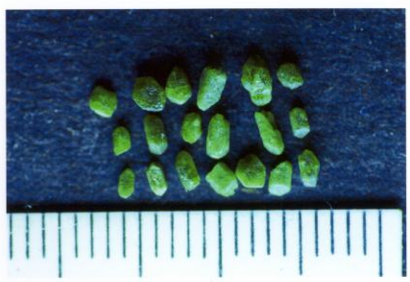


HD - 4.4 mm

XPL Micrographs
Bastnäsite in Carbonatite
Mountain Pass, CA

Monazite REE PO_4 70% REO

Normal Light

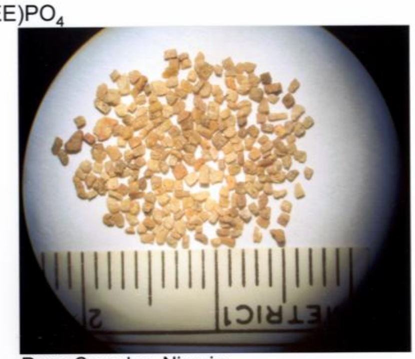


Unfiltered Shortwave UV

Beach Sands, River Placers, Metamorphic Rocks, Carbonatites
Beach Sands byproduct of Ti and Sn Mining
May be very high in Th
May have major Nd
Potential Source in Carbonatites
Kangankunde, Malawi
Wicheeda Lake, British Columbia

Xenotime (Y,HREE)PO_4

Thailand
Morphology – Tetragonal Dipyramids



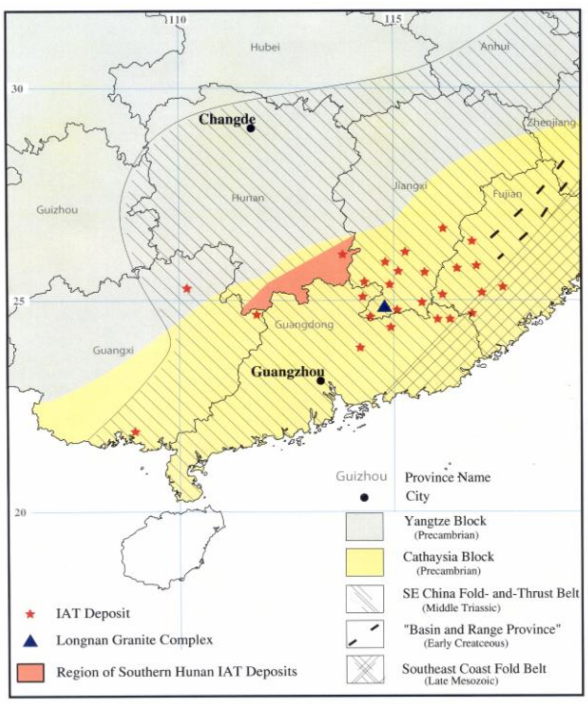
Ropp Complex, Nigeria
Morphology – Tetragonal Platelets

Xenotime, one of the best sources for Y and HREE is found in small quantities, most often with larger quantities of monazite, in granitic, pegmatitic, gneissic rocks and in stream and beach placers. Un-sastained concentrates are periodically produced in cassiterite and ilmenite mining of beach sands from Thailand, Indonesia, Malaysia, and Australia.

Approximately 300,000 tons of xenotime is reported to occur in the North "T" Zone of the Thor Lake deposit in the NWT of Canada.

Hydrothermal vein mineralization of xenotime in quartzites occurs in the John Galt deposit of Western Australia and in the Wheeler River "Maw Zone" of the Athabaska Basin, Saskatchewan.

Xenotime is also reported together with synchysite (Y) in peralkaline syenites and nepheline syenites of AK-Tuz: Kyzyl-Ompul, Kyrgyzstan.



Xunwu Longnan District, Jiangxi Province, China

Ion Adsorbed Clays Mining Procedure

1) The lateritic ore is a whitish colored regolith soil that is mined from nearby hills. Surface areas have been exposed by removal of trees and vegetation. The ore extraction may be selective along bands that are lighter than adjacent soil. This could be fracture dependant where lateritic weathering has been more advanced.

2) Somewhere nearby pits are dug and plastic linings placed in the pit bottoms to prevent escape of fluids. Pits are filled with water and ore. The pit material is then exposed to leaching with H_2SO_4 or ammonium sulfate, whereby the REE are put into solution.

3) The fluids are later siphoned downhill into another concrete pool.

4) These fluids are exposed to oxalic acid, and REE oxalates are then precipitated.

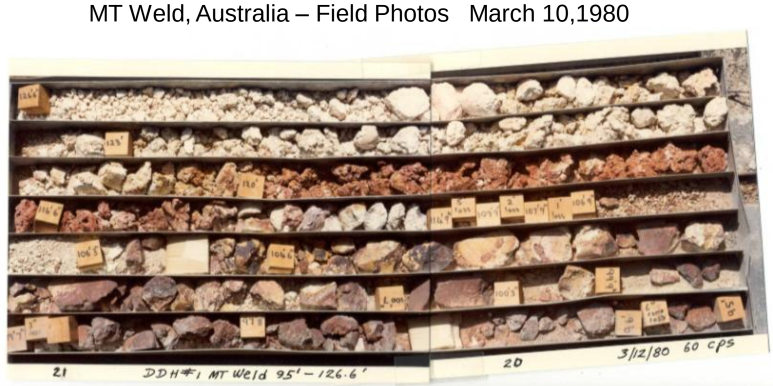
5) The precipitate is collected into a calcining kiln and fired up at 800°C.

6) The end product is stored into bags containing ≈ 92% REO.

Supergene REE Mineralization

A major source of REE and Y occurs in the weathered carbonatite laterites where weathering that may exceed 300 meters causes the chemical breakdown of primary minerals (*calcite, dolomite, apatite*) and their release of REE and Y which subsequently recrystallize forming high-grade secondary mineralization. The supergene products include monazite, gorcexite, goyazite, florencite, churchite, and xenotime as vast accumulations inextricably associated with iron oxides and other residual accumulations.

MT Weld, Australia – Field Photos   March 10,1980



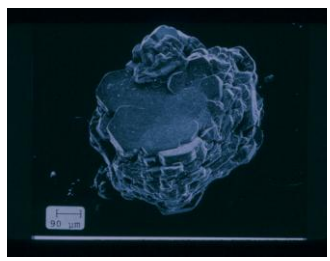
MT Weld Drill Core where supergene REE mineralization was first identified - March 13,1980

MT Weld, Western Australia – Open Pit REE Mine

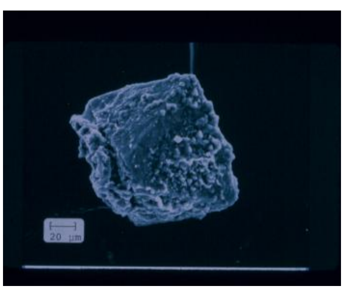
Photo by Clint Cox
February 2010.

Clint Cox
c.cox@theanchorhouse.com
(847) 682-2805 mobile

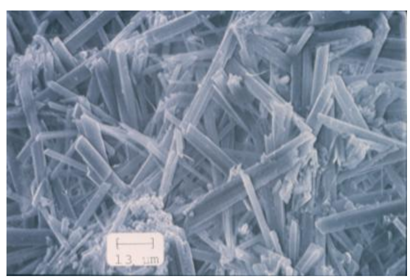
Monazite pseudomorph after apatite



Monazite pseudomorph after Rhabdophane



Florencite pseudomorph after pyrochlore



Churchite $YPO_4 \cdot 2H_2O$

Supergene Minerals – MT. Weld, Australia

Supergene REE Occurrences Include …..

MT. Weld, Australia

Araxá, Minas Gerais, Brazil

Catalão, Goias, Brazil

Mrima, Kenya

Mabounié, Gabon …..

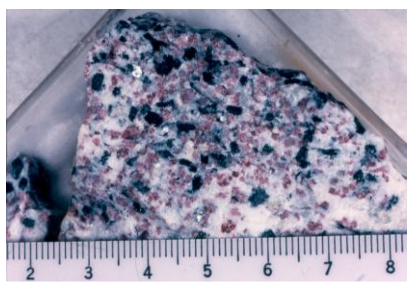
and other more remote occurrences in the South American Amazon and in Siberia.

Despite their high-grade and large tonnage, none of these occurrences have yet been exploited.

There is no conclusive evidence that the REE and Y can be extracted from the supergene minerals on an economic level that can compete with the current world market sources.

Eudialyte $Na_{15}Ca_6(Fe^{2+},Mn^{2+})_3Zr_3(Si,Nb)(Si_{25},O_{73})(O,OH,H_2O)_3(CL,OH)_2$

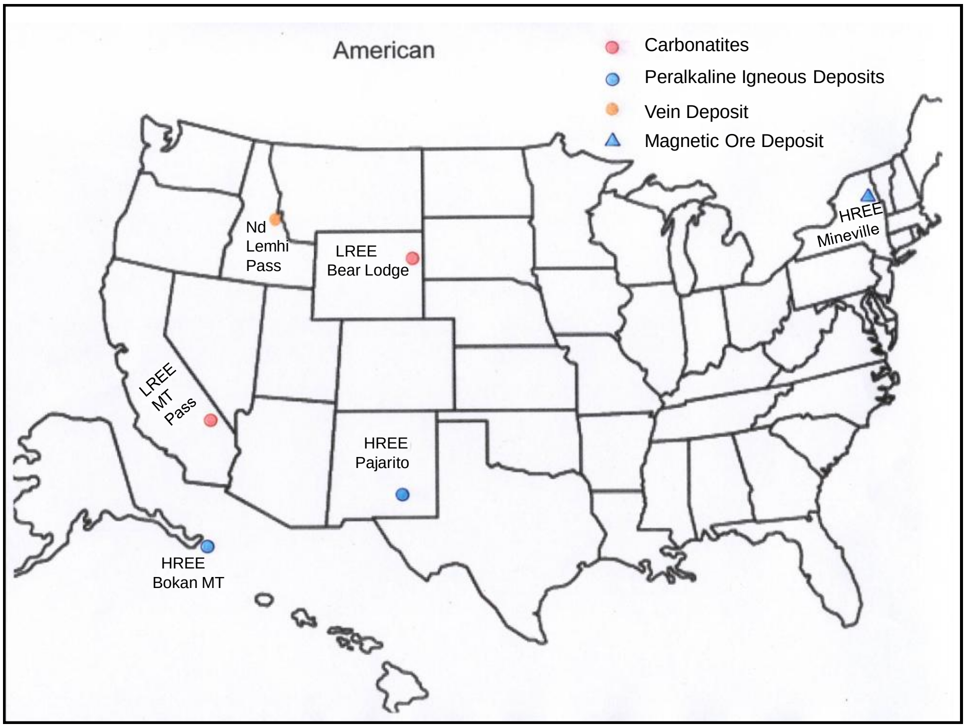
Red Wine Complex, Labrador

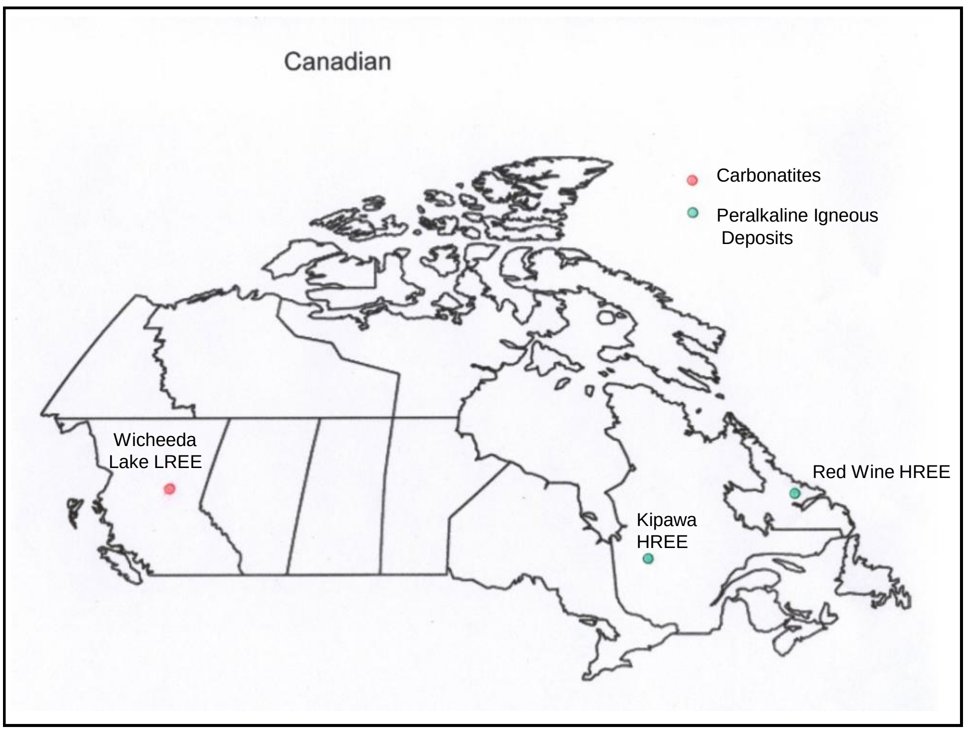


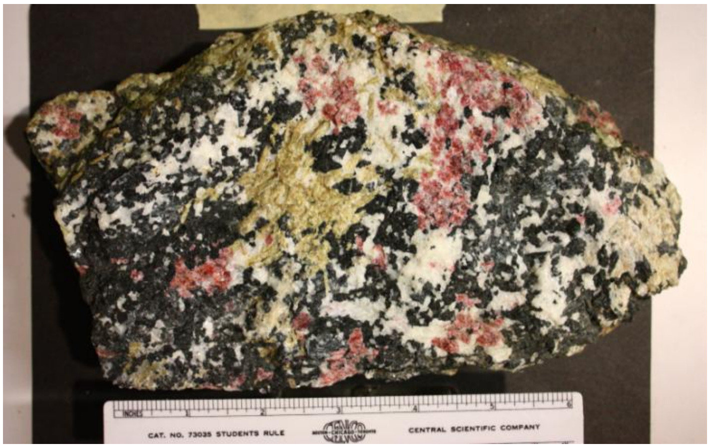
Dora Bay, Alaska

Kipawa, Quebec

Eudialyite may also contain Y and HREE in amounts exceeding 4 wt.%. The mineral is easily dissolved in weak acids but colloidal silica currently presents a problem in the isolation of Y, REE and Zr oxides.

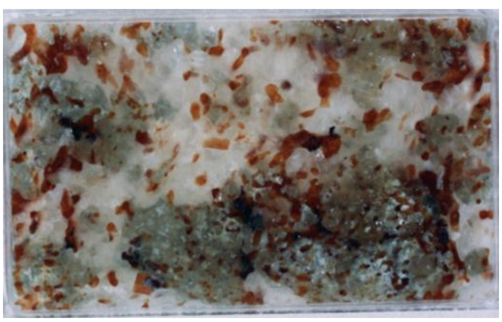

American
Carbonatites
Peralkaline Igneous Deposits
Vein Deposit
Magnetic Ore Deposit
Nd
Lemhi
Pass
LREE
Bear Lodge
HREE
Mineville
LREE
MT
Pass
HREE
Pajarito
HREE
Bokan MT


Canadian
Carbonatites
Peralkaline Igneous
Deposits
Wicheeda
Lake LREE
Red Wine HREE
Kipawa
HREE



Eudialyte and Mosandrite in Peralkaline Syenite

Kipawa, Quebec



Britholite-Rich Skarn

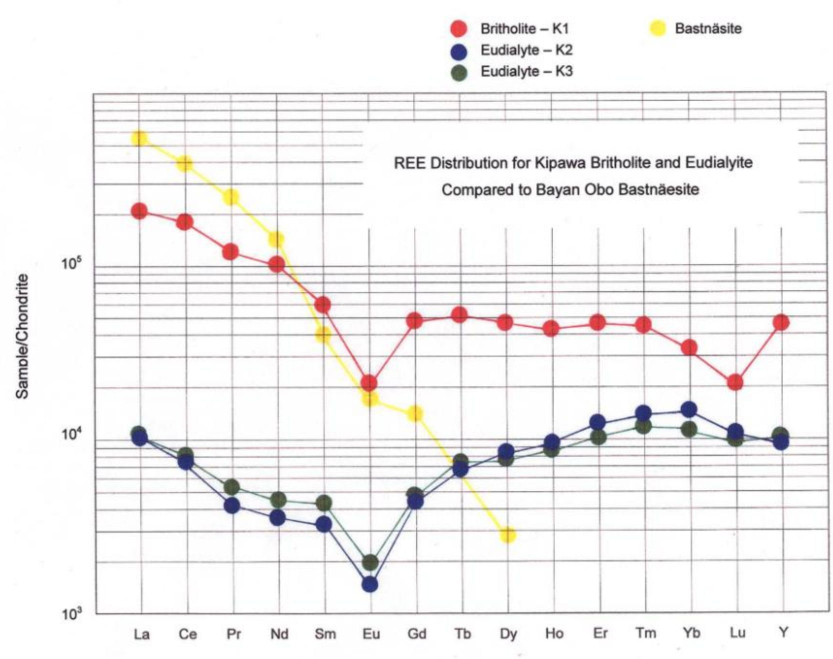
All brown prisms are britholite

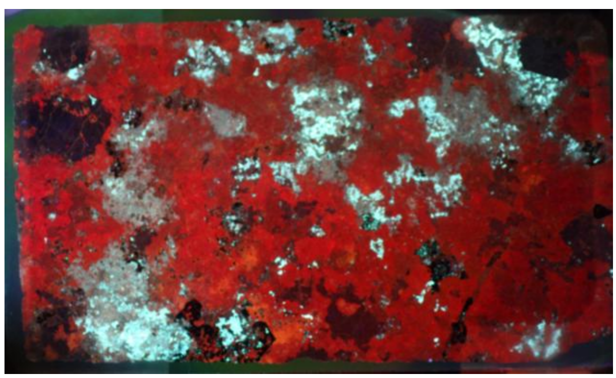
(Horizontal Distance – 46 mm)

Britholite Concentrate (mm scale)

Britholite – $(Ce,Y,Ca)_5(SiO_4 \cdot PO_4)_3(OH,F)$

Kipawa, Quebec



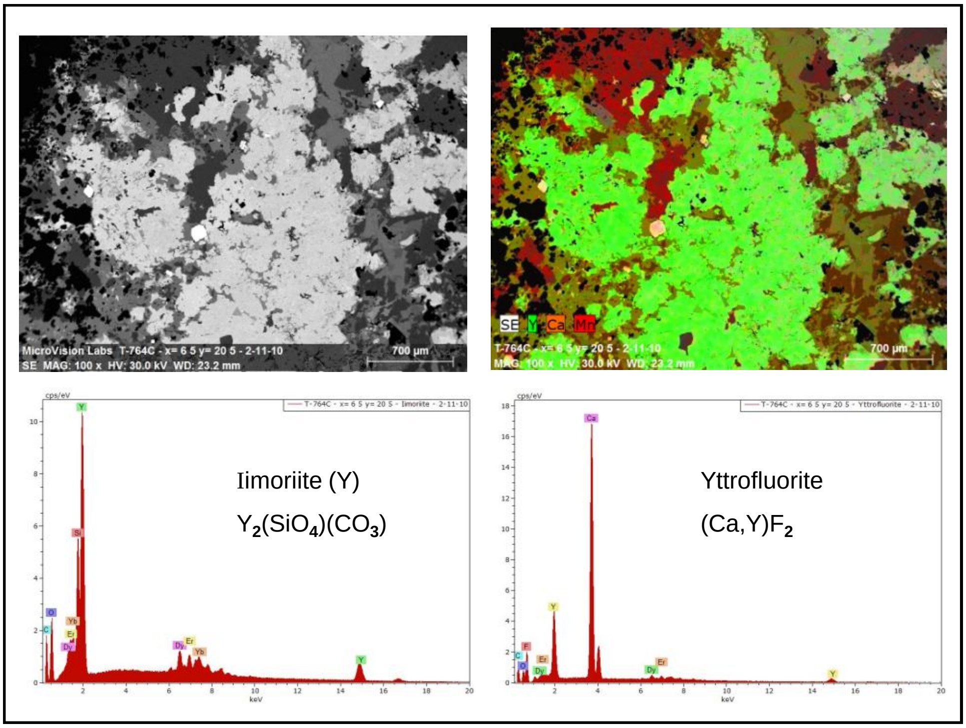


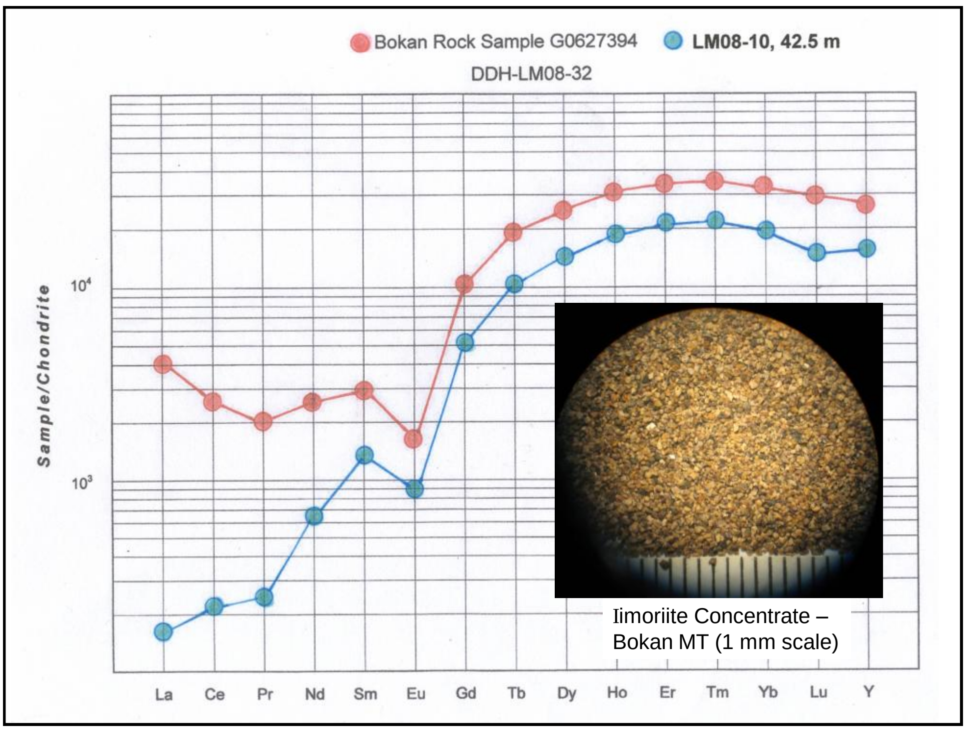
Cathodoluminescence Macrograph of Iimoriite in Syenite – Bokan Mountain

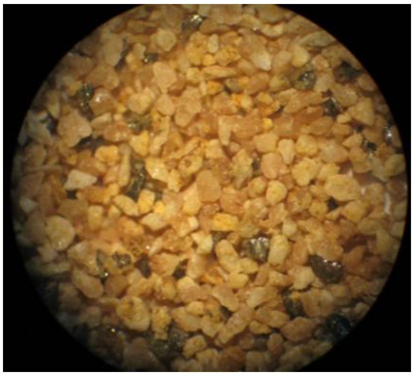
Mottled light blue and tan clusters - Iimoriite

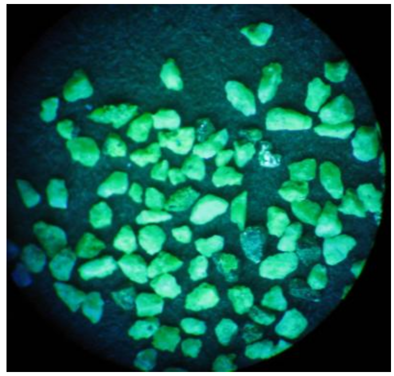
Red groundmass – Feldspar

(Horizontal distance of rock slab – 46 mm)


MicroVision Labs T-764C - x= 6 5 y= 20 5 - 2-11-10
SE MAG: 100 x HV: 30.0 kV WD: 23.2 mm
700 µm
SE Y Ca Mn
T-764C - x= 6 5 y= 20 5 - 2-11-10
MAG: 100 x HV: 30.0 kV WD: 23.2 mm
700 µm
Iimoriite (Y)
$Y_2(SiO_4)(CO_3)$
Yttrofluorite
$(Ca,Y)F_2$
cps/eV
keV


Bokan Rock Sample G0627394
LM08-10, 42.5 m
DDH-LM08-32
Sample/Chondrite
10^4
10^3
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Y
Iimoriite Concentrate –
Bokan MT (1 mm scale)





Wicheeda Lake Heavy Mineral Composite — *(from samples 828951, 52, 53)*

These grains range in size between 0.2 and 0.5 mm. The left micrograph consists of major monazite and parisite and minor grains of pyrite. Dolomite is also attached to some of these grains. The right micrograph shows selective reflection of the green part of the visible spectrum under unfiltered shortwave UV examination. This test is diagnostic for the identification of LREE minerals.

As a final statement it should be emphasized…

- 1) Carbonatites containing as much as 5 wt. % LREE must compete with Bayan Obo, Maoniuping, and Mountain Pass which have much higher grade, and have established physical and chemical processing plants.
- 2) Deposits that are mineralized with allanite and LREE-enriched apatite can not compete economically with Mountain Pass and Bayan Obo.
- 3) Although ion-adsorbed REE in clays from South China provide the bulk of HREE to the market place, in other countries, high costs for labor and necessary supplies, power costs, and environmental restrictions may render similar deposits uneconomical.

Paper, James C. Lancaster,
Selling the Nation's Helium Reserve

Selling the Nation's Helium Reserve

James C. Lancaster, National Research Council

I will be discussing some of the findings and recommendations reached in a recent study conducted by the National Research Council (NRC) regarding the federal helium reserve, focusing on those aspects of the study that relate to this workshop and the APS study to follow. Helium has long been the subject of public policy; hopefully this discussion will provide an historical perspective of how the federal government has dealt with scarce materials such as helium in the past and the recent NRC study will help to stimulate ideas on how to respond to some of the issues faced by this study.

After briefly describing the history of the federal helium reserve and the events leading up to our study, this paper discusses aspects of the demand and supply sides of the helium market that raise policy implications. It concludes by setting out some of the recommendations reached by the committee in responding to the current state of affairs.

Introduction

The Bureau of Land Management (BLM) manages the nation's federal helium reserve, which consists of crude helium stored in a naturally occurring underground structural dome located outside of Amarillo, Texas and an extensive pipeline system that connects the dome to crude helium extraction plants and helium refining plants located in Kansas, Oklahoma, and Texas. This helium storage facility was established as part of cold war efforts in the 1960s to provide helium for the rapidly expanding needs of defense, the new space program, and scientific research. As part of those same efforts, the federal government encouraged the private sector to develop helium extraction and refining capacity and purchased crude helium that was produced. Those efforts were quite successful. By the early 1970s over 35 billion cubic feet (Bcf) of helium had been bought by the federal government and deposited into the dome. Given that annual helium usage at the time was approximately 650 million cubic feet (MMcf), this represented the accumulation of an approximately 50 year supply of helium. Given the size of the amount in reserve, the federal government quit purchasing significant amounts of helium in the mid-1970s and for the next 20 years, the amount of helium on deposit remained fairly constant.

In 1996, Congress enacted legislation that manifests current public policy regarding helium. That Act directs BLM to sell off substantially all federally owned helium by the year 2015 at prices that would repay the federal government its costs in purchasing the crude helium and maintaining the system, plus interest. In 2003, BLM began offering helium for sale pursuant to the 1996 Act. Even though the price at which BLM was required to sell the helium was significantly higher than the price of privately owned helium, there was a ready market for the federal helium. Shortly after the sell-off began, retail prices for helium began to rise.

As a result of widespread helium shortages and significant price increases that occurred in 2006 and 2007, BLM commissioned the current study from the NRC. The principal charge to the committee was to determine "whether selling off the U.S. Helium Reserve in the manner prescribed by law has had any adverse effect on U.S. scientific, technical, biomedical, and national security users of helium,"[1] and if so, to recommend steps to be undertaken to address those adverse effects. The committee was co-chaired by Chip Groat, former head of the U.S. Geological Survey and now Dean of the Jackson School of Geosciences at the University of Texas at Austin, and Bob Richardson, a Cornell University physicist who was awarded the Nobel Prize in physics for his work with superfluid helium-3.

Sources of Helium

Helium actually is the second-most-abundant element in the universe, but because of its high diffusivity is fairly rare on Earth. The amount of helium in the atmosphere is approximately 5 parts per million, with this concentration constituting the steady state balance between continuous production through decay of radioactive material in the Earth and its diffusive loss to space. Using current technology, it is not economically feasible to extract helium from air. Rather, the principal sources of helium are natural gas fields where helium generated by radioactive decay has been trapped by the same relatively impenetrable strata that trap the natural gas. These gases primarily consist of methane, smaller concentrations of ethane, propane, butane, and other hydrocarbons, as well as various contaminants such as H_2S, CO_2, and He.

Current technology requires that a critical threshold of 0.3 percent of helium be present in a natural gas field before it is economically feasible to process the gas for helium. Most of the known pockets of gas that meet this criterion are located in the United States and historically, almost all of the helium that has been produced has come from gas fields located in the mid-continental parts of North America. These gas fields principally consist of methane and are produced for their energy content. The dome containing the federal helium reserve and connecting pipelines that are discussed in the introduction are located in this area.

Within the last few decades, several gas fields in Wyoming have come into production and are being exploited for their non-energy-related components—principally He and CO_2. Included is a facility at Riley Ridge owned by Exxon-Mobile that currently is the largest producer of helium in the world. At peak capacity, it can produce approximately 1.5 Bcf of helium per year. See Figure 1 for the location of the principal domestic sources of helium.

Very recently, a third source of helium has been developed in conjunction with significant increases in global capacity for producing liquefied natural gas (LNG). These facilities, located or being built in countries such as Algeria, Qatar, and Russia, take advantage of the fact that after the hydrocarbons have been liquefied, the left-over gas has a high concentration of helium, often as much as 50 to 60 percent. With the

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[1] Statement of Task – Appendix A, *Selling the Nation's Helium Reserve*, National Academies Press: Washington, D.C. (2010).

maturation of the mid-continental gas fields, these foreign sources are destined to produce an increasingly higher percentage of the helium that will be on the market.

Finally, because of the legislatively directed sell-down of the helium reserve, the federal government has become a significant, though temporary, source of helium. It currently satisfies over one-half of the annual U.S. demand for helium and supplies approximately one-third of the annual global consumption.

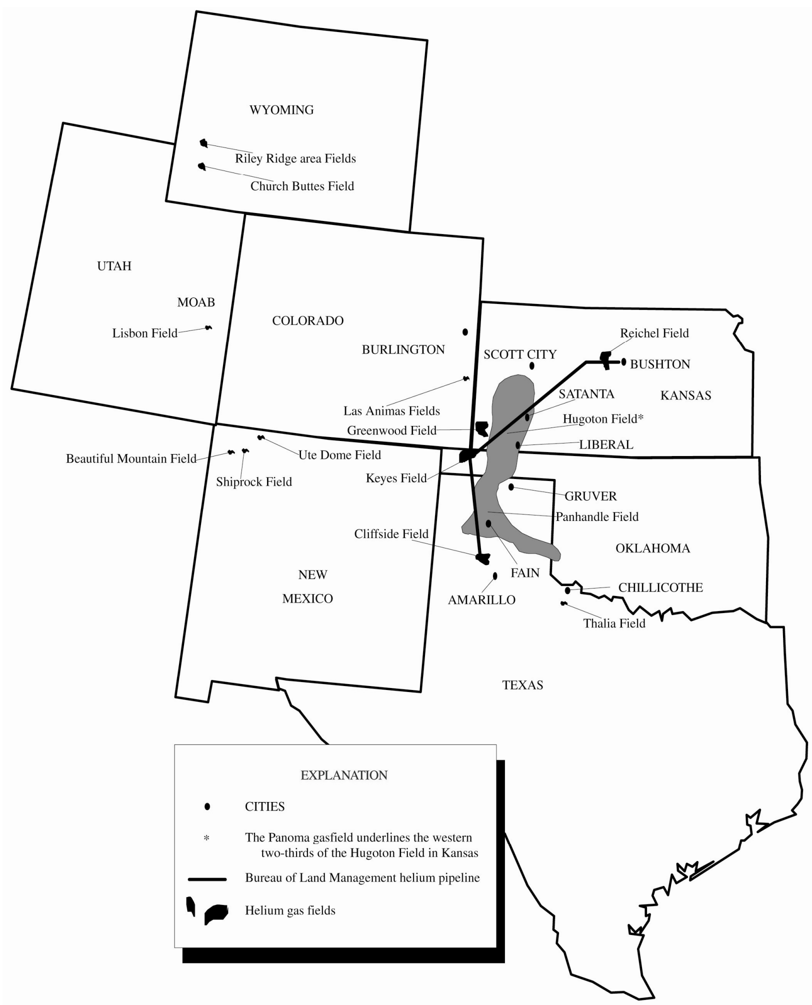

Figure 1 – Domestic sources of helium. SOURCE: United States Geological Survey, 2006 Minerals Survey, Helium.

Policy Ramifications Associated with Helium Sources

Several aspects of the supply side of the helium market complicated the committee's efforts in making findings and developing recommendations. The first complicating factor arises from the fact that helium is a derived product: Its availability principally depends on the production of other products. One important consequence is that the market can't simply respond to increased demand with increased output. Any increase in output requires, at a minimum, additional sources of natural gas with concentrations of helium at the threshold level of 0.3 percent or higher. As importantly, helium reserves are not like natural gas or oil reserves in the sense that the reserve remains in place until economic or other considerations justify recovery. Development of a natural gas field will depend almost entirely upon the demand for the primary product. Even for natural gas deposits with a relatively high percentage of helium, the helium in that gas will be lost when the natural gas is extracted unless significant investments have been made in complementary helium extraction facilities.

The second major complicating factor is that helium is a niche market with high barriers to entry. The helium market is highly specialized, with far fewer customers and dollars generated than markets for natural gas and crude oil. It also requires specialized and expensive equipment to produce and transport the helium. As a result, essentially all crude helium is refined and made available to the rest of the supply chain by a very limited number of companies. One important consequence is an opaqueness to this side of the market that makes it difficult to assess the market and how it might respond to different scenarios. A related concern is that very little information is available about current reserves and potential future sources of helium, especially overseas.

The final complicating factor is the existence of the federal helium reserve itself. Any significant change in the amount of helium supplied from the reserve could greatly impact helium's availability and pricing. The committee was required to take all of these factors into consideration in developing its recommendations.

Uses of Helium

Current global consumption of helium is approximately 5.5 to 6 Bcf, with domestic consumption approximately half of that volume. Helium is somewhat different from many of the other materials being considered in this study in that the range of uses for helium is quite impressive. See Figure 2 for a graph of the principal areas in which helium is used.

This array of uses stems from helium's unique physical and chemical characteristics—specifically, its stable electronic configuration and low atomic mass. Helium has the lowest melting and boiling points of any element: It liquefies at 4.2 Kelvin and 1 atmosphere and solidifies only at extremely high pressures (25 atmospheres) and low temperatures (0.95 Kelvin). As a result, there are many cryogenic applications for helium, which make up the largest single category of applications by percentage of helium consumed. These include scientific applications such as creating the ultracold environment needed to study quantum effects of materials and cooling the superconducting magnets used in accelerators and high magnetic laboratories. The development and production of magnetic resonance imaging (MRI) devices for the medical field also consumes significant amounts of helium for cooling the superconducting magnets used in those devices.

The closely related category of pressurizing and purging is the second largest usage of helium and principally encompasses activities by the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD) in developing and using liquid-fueled rockets. For several reasons, only helium can effectively be used to purge and pressurize these systems. In LH_2 environments, all gases other than helium and hydrogen would freeze, clogging fuel lines and systems and rendering the rocket engines nonfunctional. Although gaseous hydrogen might have the right physical properties for use in LOx systems, its reactivity with oxygen precludes its use.

As the second lightest element, gaseous helium is much lighter than air, causing it to be quite buoyant. When combined with its chemical inertness, helium's buoyancy makes it an ideal lifting gas. Uses that depend on helium's lifting capability include military reconnaissance, weather monitoring, and party balloons. Other applications draw on other characteristics of helium—its relatively high thermal conductivity, low viscosity, and high ionization potential—either alone or in combination. These applications include welding, providing controlled atmospheres for manufacturing operations, and detecting leaks in equipment providing vacuum environments to science and industry.

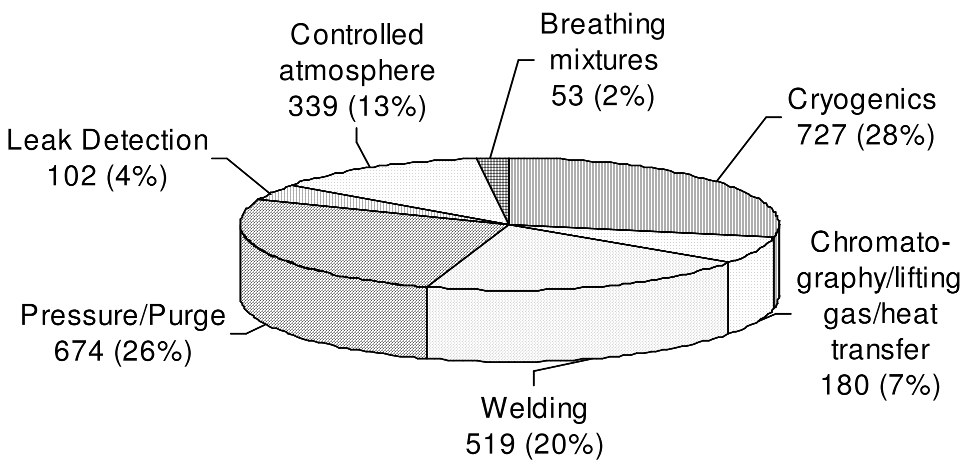

FIGURE 2 Estimated end uses of helium in the United States for 2006. The shares are the percent of U.S. consumption by volume with the annual volume consumption given in million cubic feet (MMcf). SOURCE: United States Geological Survey, 2006 Minerals Survey, Helium.

Currently, most of the energy-related uses of helium are indirect. However, like other materials being discussed at this workshop, future uses of helium are being considered in the energy sector that potentially raise scarcity issues. For helium, it is use in the next generation of nuclear reactors. Several companies have been developing high- or ultra-high-temperature nuclear reactors that use gaseous helium as the thermal conduit between the nuclear-reacting heat source and an energy-generating turbine. What helium offers to these systems is high thermal conductivity; inertness—helium doesn't readily chemically react with other material; and the lack of reactivity effects—neutron radiation doesn't make helium radioactive. These attributes allow the reactors to operate at significantly higher temperatures than current reactors, with the increased efficiencies that those higher temperatures allow.

So, what are the helium demands of such a system and what are the limits in scaling-up these systems? Pebble Bed Modular Reactor, Ltd. (PBMR), a South African company developing its own version of this type of facility, supplied information that addresses some of these issues. According to PBMR, a unit capable of producing 500 MW of thermal power will require 2 million cubic feet (MMcf) of helium to start up and will have helium losses of about 20% each year. If one assumes that the plant produces an average annual output of 94% of its installed capacity and has the expected 40% efficiency in converting thermal power to turbo-generator output, then each facility can provide 1.6 million MWh of electricity per year.

The electricity that could be provided and the associated effects on the availability of helium from such a resource can be evaluated under varying scenarios, based upon the roughly 6 Bcf of helium globally consumed each year and the annual global electrical demands of approximately 20 Million GWh. As an example, 150 of these units would require about 5 percent of the annual global helium supply in their initial setup and annually demand about 1 percent of current helium supplies to replenish for losses. Those 150 units would satisfy about 1.25 percent of current electricity demand. 12,000 of these facilities would be needed to meet 100 percent of current annual global electricity demands. That number of facilities would consume about 5 Bcf of helium each year—most of the helium currently being produced—and the amount of helium needed to start up that number of facilities would be approximately four times the amount of helium currently consumed each year worldwide.

The other direct role that helium might play with respect to energy is its use in superconducting electricity transmission. Approximately 6-7% of produced electricity is consumed through resistive losses in transmitting the electricity from generators to end users. One proposed solution for partially addressing this issue is to incorporate superconducting (non-resistive) transmission elements in areas of heavy power transmission. Unfortunately, all material currently capable of being superconducting must be cooled with helium to reach a superconducting state. At current prices of electricity and helium, this potential solution is cost-prohibitive.

Policy Ramifications Associated with Helium Uses

The demand side of the helium market also raises issues that the NRC committee was required to take into account in developing its findings and recommendations. The first general set of issues arises from the fact that the broad range of applications for helium creates a very complicated picture when one is attempting to assess how different policies might affect national interests. Obviously, some uses are more important than others from the standpoint of our nation's critical interests. For some uses such as welding, there are ready substitutes for helium, while other applications rely on helium's unique properties and there are no alternatives. Technologies are available and can be readily implemented by some helium users that would reduce the amount of helium they consume by as much as a factor of ten and help ameliorate the consequences of limited supply and high prices. Other users find it difficult if not impossible to implement conservation steps.

Pricing changes affect groups of users differently. For many of the industrial, biomedical, and larger national-security-related users, rising costs are important but do not threaten the viability of their operations. Small-scale scientific laboratories at U.S. universities and national laboratories are the principal exception. For many of these laboratories, helium is a significant fraction of their costs. Large increases in helium prices over a short time frame threatens their ability to continue to conduct research since the funding mechanisms for these laboratories simply are not designed to respond to these types of price shifts.

The second general set of issues associated with the demand side of the helium market is the paucity of available information. The only publicly accessible information about the uses of helium is gathered by BLM and it only relates to domestic usage. To collect that information, BLM relies upon the good graces of those few companies that process and sell helium to provide it information about their customers. The information is only updated approximately every three years and contains no information about pricing but only about how much helium has been supplied to end users in the broad categories shown in Figure 2. No detailed information is available about helium usage outside of the United States.

Committee's Recommendations and Conclusion

Of the recommendations made by the committee, several have resonance with the issues being addressed by this workshop. As previously mentioned, one of the difficulties encountered by the committee was the lack of timely and sufficient information to evaluate the supply and demand sides of the helium market, especially non-U.S. supply and demand. Because the committee believed such information to be critical for formulating and carrying out policies with respect to helium, it recommended that

> **BLM should acquire, store, and make available to any interested party the data to fill gaps in . . . information on the helium content of gas reservoirs throughout the world, including raw data, methodology, and economic assessment that would allow the classification of reserves contained in specific fields, and . . . trends in world demand. BLM or other agencies with the necessary expertise, such as the U.S. Geological Survey, should develop a forecast over the long term (10-15 years) of all U.S. demand for helium for scientific research and for space and military purposes.**

One of the critical findings by the committee is that the helium market is rapidly changing. Many of the current industrial uses of helium, such as optical fiber manufacturing and MRIs, are very recent developments and were not foreseen in previous studies. The amount of helium that appears to be available in conjunction with LNG facilities is also a recent development. In addition, because the federal helium reserve is so large, steps undertaken in connection with it can have unintended consequences. Because of these factors, the committee recommended the development of a more permanent and sustained plan for managing helium -

> **BLM should form a standing committee with representation from all sectors of the helium market, including scientific and technological users, to regularly assess whether national needs are being appropriately met, to assist BLM in improving its operation of the Federal Helium Reserve, and to respond to other recommendations in this report.**

Finally, given the critical role that helium plays in so many critical areas, the committee believed that Congress should revisit the concept behind the privatization efforts of the mid-1990s and made the following recommendation -

> **The congressional committee or committees responsible for the federal helium program should reevaluate the policies behind the portions of the 1996 Act that call for the sale of substantially all federally-owned helium on a straight-line basis. It or they should then decide whether the national interest would be better served by adopting a different sell-down schedule and retaining a portion of the remaining helium as a strategic reserve, making this reserve available to critical users in times of sustained shortages or pursuant to other predetermined priority needs.**

Response to the report has been quite positive. The co-chairs of the committee, Chip Groat and Bob Richardson, have briefed staff from the sponsoring agency, agencies that support scientific research, the Office of Science and Technology Policy, and the Office of Management and Budget, as well as staff members for two House committees and one Senate committee. Finally, the House Subcommittee on Energy and Natural Resources has scheduled a committee hearing to take testimony regarding the issues raised by the report, with the expectation that legislation will be considered that will address some of the outstanding issues associated with the helium reserve.

Presentation, Cyrus Wadia,
Mined Resource Constraints on Solar Energy and Battery Storage Potential

Mined Resource Constraints on Solar Energy and Battery Storage Potential

Cyrus Wadia
Lawrence Berkeley National Lab
April 29th, 2010
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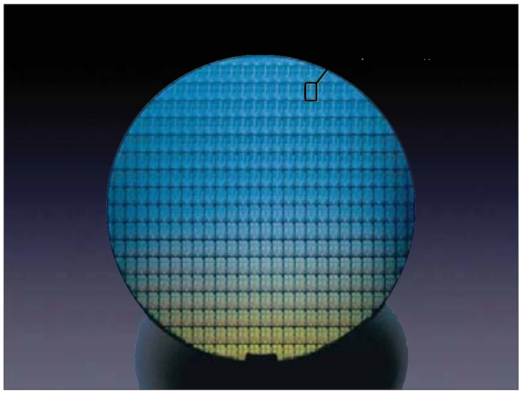
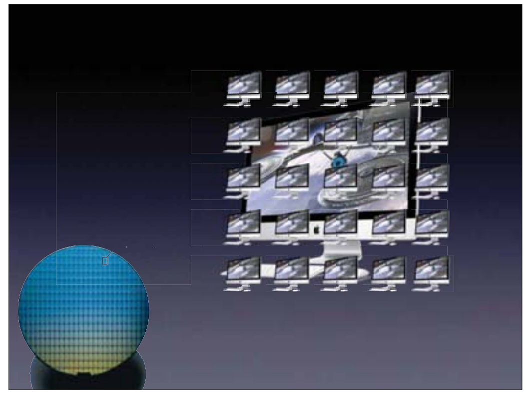
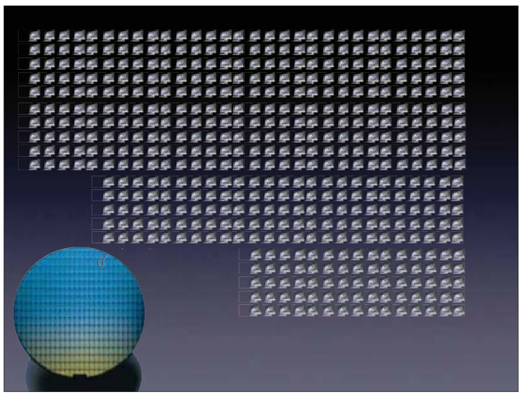
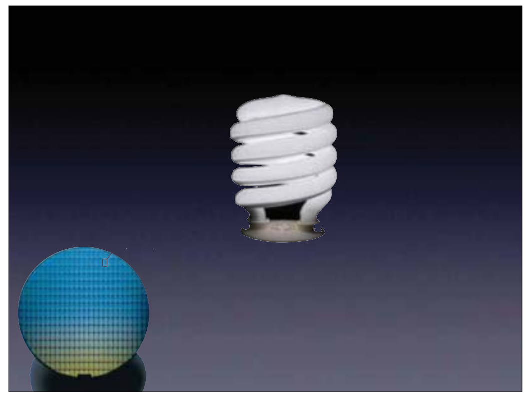
- Introduction of research and current responsibilities
- R&D Analysis for Photovoltaics (sulfides, oxides, In, Te, Ga, Si)
- Limitation Analysis for Electrochemical Storage (REE, Li, Co)










COST
SCALE
El Sobrante
Richmond
Albany
Berkeley
Orinda
Lafayette
Emeryville
Moraga
Tiburon
Belvedere
Corte Madera
San Francisco
Alameda
Oakland
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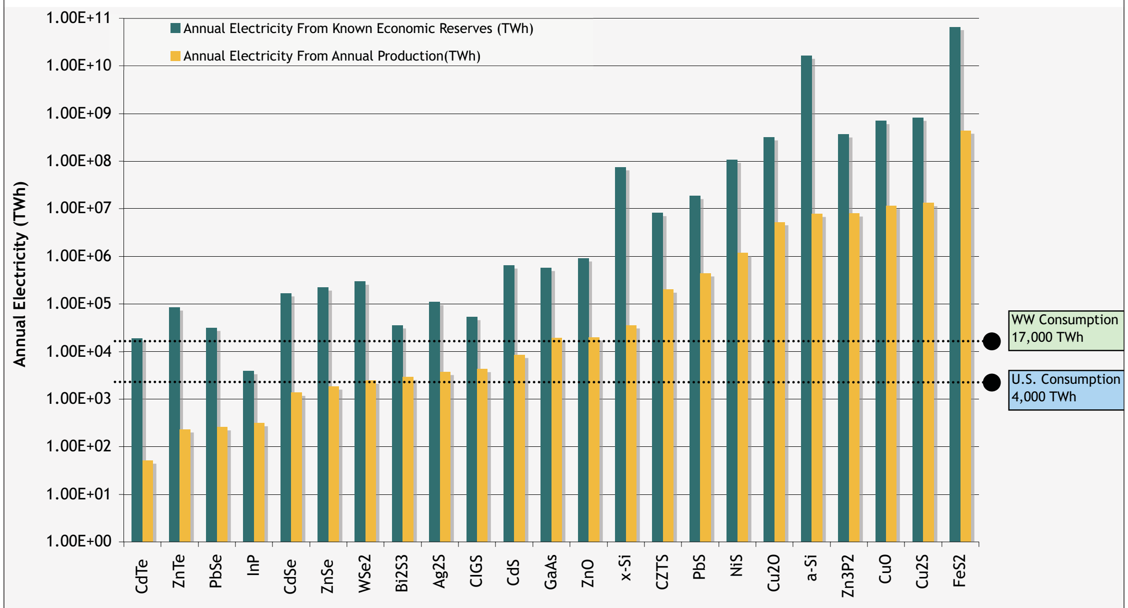
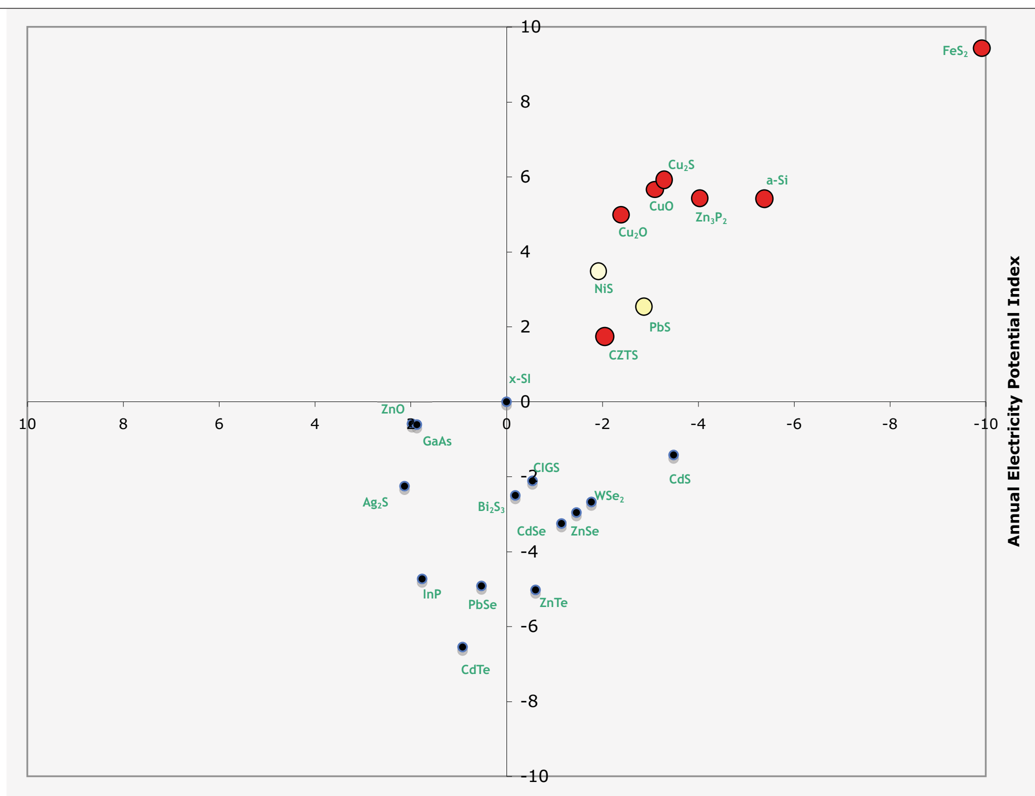


Source: Wadia, Alivisatos, & Kammen, Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment, *Environ. Sci. Technol.* 2009, 43



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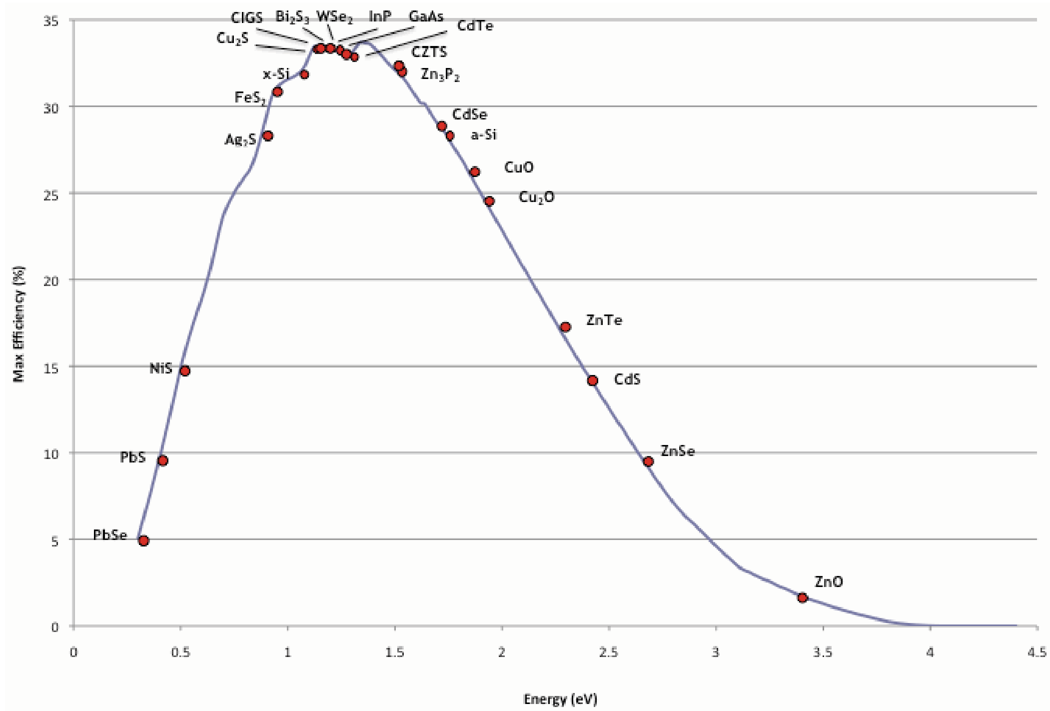

Wadia, Alivisatos, & Kammen, Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment, *Environ. Sci. Technol.* 2009, 43

	Tag	Negative	Positive	Limiting Element (reserves & ann prod)	Common name	E_{theor} (Wh/kg)	E_{pract} (Wh/kg)	Additional remarks
Aqueous	1	Pb	PbO2	Pb	Lead acid	252	35	Mature technology; extensive recycling programs in place. Deep discharge causes sulfation, which lowers cycle life. Life is around 5 years.
	2	Zn	AgO	Ag		524	105	Zn shape change limits life, and dendrites are a risk.
	3	Cd	Ni(OH)2	Cd	NiCd	244	35	Mature technology. Stable and safe, with a good life.
	4	REE	Ni(OH)2	REE	Ni/MH	240	75	Mature technology. Stable and safe. Life up to 15 years depending on application and use.
	5	La	Ni(OH)2	La	Ni/MH	240	-	
	6	Zn	Ni(OH)2	Ni		372	60	Zn shape change limits life, and dendrites are a risk.
	7	Zn	MnO2	Mn	Alkaline	358	85	Currently the dominant primary cell. Zn electrode has the same problem of shape change.
Lithium ion (organic)	8	Li4Ti5O12	LiCoO2	Co		241	110	A low-energy but stable lithium-ion cell.
	9	Si (alloy)	LiCoO2	Co		861	-	The Si alloy negative electrode is currently under development. The stability and round-trip current efficiency are relatively poor.
	10	Li	LiCoO2	Li		1023	-	Li metal forms dendrites and causes shorting. Development work is focuses on eliminating dendrites.
	11	C6	LiCoO2	Co	Lithium ion	614	220	The dominant lithium-ion chemistry. Life is limited by side reactions and high temperatures; life is typically 2-3 years, but depends on application and control methods.
	12	C6	LiMn2O4	Mn		330	150	At high temperatures Mn can dissolve and limit life.
	13	C6	LiNi0.80Co0.15Al0.05O2	Li		636	250	LiNi0.80Co0.15Al0.05O2 is a "next generation" positive electrode material.
	14	C6	LiNi0.33Mn0.33Co0.33O2	Mn		646	250	LiNi0.33Mn0.33Co0.33O2 is a "next generation" positive electrode material.
	15	C6	LiFePO4	Li		385	110	LiFePO4 is a low energy positive electrode with the potential to be inexpensive and safe.
	16	C6	LiMnPO4	Mn		469	-	LiMnPO4 is an experimental positive electrode.
High temp. (other)	17	Li	S	Li		2600	350	In the high-temperature form alloy electrodes are often used, such as LiAl/FeS or LiAl/FeS2, the operating temperature is 375-500C, and the cycle life is good. An ambient-temperature cell is also under development,
	18	Na	NiCl2	Ni	Zebra	787	115	Needs special containment for high temperatures and high-purity materials. Runs at 270 to 350C to keep active materials liquid and electrolyte conductive. Good cycle life for charge and discharge.
	19	Na	S	Na	NAS	792	170	Needs special containment for high temperatures and high-purity materials. Runs at 270 to 350C to keep active materials liquid and electrolyte conductive. Good cycle life, but a limited number of thermal cycles.
	20	Mg	Sb	Sb		254	-	An experimental all-liquid battery for high-current grid-storage applications.
Flow cells (other)	21	V2O5 (3+)	V2O5(4+)	V	Vanadium flow cell	29	10	Requires a proton-exchange membrane. Upper temperature limited to 50C due to precipitation. Good life.
	22	Zn	Br2	Br		429	65	Problems with Br crossover and Zn dendrites. Uses an aqueous electrolyte and operates at ambient temperatures.
	23	Na2S2	NaBr3	Br	Regenysys flow cell	41	20	Problems with electrolyte crossover
	24	CrCl3	FeCl2	Cr		99	-	Problems with electrolyte crossover.
	25	ZnO	Ce2(CO3)3	Ce	Plurion	60	-	Uses Nafion membrane. Design may also include a Pt-Ti mesh cathode.
Metal air (other)	26	Zn	O2	Zn		866*	350	Used as primary cell in small formats (hearing-aid batteries); may be mechanically or electrically recharged. Electrical recharge is limited by the poor kinetics of the air electrode and the absence of a suitable bipolar catalyst.
	27	Li	O2	Li		3622*	-	Experimental system that uses a polymer electrolyte and an oxygen-permeable membrane. Contaminants must be kept out of the cell to prevent degradation. Electrical recharge is limited by the poor kinetics of the air electrode and the absence of a suitable bipolar catalyst.

* based on the discharge product (ZnO and Li_2O_2)

White Paper, Scott F. Sibley,
Supply of and Demand for Selected Energy Related Mineral Commodities

Supply of and Demand for Selected Energy Related Mineral Commodities

by
Scott F. Sibley
U.S. Geological Survey

In this report, subjects discussed include components of mineral supply, production, and consumption data, and information on selected mineral commodities in which the Energy Critical Elements Study Group has an interest, and U.S. Geological Survey (USGS) recycling studies, with some results of these studies.

MINERAL SUPPLY

Supply is composed of primary material, which may be either a principal product or byproduct of a mining operation, and secondary, composed of new and old scrap. New scrap is material returned from a manufacturing plant—material which has not yet been used. Old scrap is post-consumer material, also referred to as obsolete scrap. This report is focused on each of the foregoing components. Industrial stocks—producer, trader, exchange, and consumer—are part of supply, but are not considered here. The supply chain includes mining, processing, and smelting or refining, and bottlenecks can occur at any point along the chain, particularly where material is produced and processed or refined in different countries.

Physical factors that could restrict mineral supply

- For many mineral commodities, and especially metals, the tonnage, grade, depth, location, mineralogy, and grain size of mineral deposits are important physical factors that affect metal supply (DeYoung and Singer, 1981, p. 940).
- If production capacity is limited and demand increases, shortages will develop and prices will increase. Molybdenum is a prime example − not enough roasting capacity caused prices to soar in 2005.
- Recycling is one of the "safety valves" in the metals market, holding down primary prices, but this supply may not be readily available. If it is and prices get high enough, scrap yards are emptied, abandoned tractors are taken out of fields, and there is theft of usable material, such as copper wire, downspouts, or even guard rails.
- Substitution is usually longer term because of design factors unless alternate material is readily substituted, such as aluminum for copper in wiring, or silver for gold in electronic contacts. Non-nickel-bearing stainless steel may replace nickel-bearing stainless steel.
- Reserves may be relatively low compared with consumption. Even if "adequate" reserves are available, long lead times can be expected for putting them into production; lead times can be even longer from the time of discovery of a deposit to its development. Exploration may take place within current mining districts or in greenfields, areas which have not experienced significant mining. Expansion

of reserves at existing deposits accounts for a large portion of additions to annual estimates of reserves.

Economic and other factors that could restrict mineral supply

- Price is a key factor influencing changes in the quantity supplied. Changes in demand will affect price, which in turn will affect exploration.
- Environmental regulations may significantly affect mining and processing costs. In addition, where regulations are strongest, development will be slower to take place or may not take place at all, in contrast to countries which have weak regulations.
- High costs, particularly energy costs, will inhibit development or even prevent it.
- Local opposition, either environmentally related or based on land sovereignty issues, such as indigenous claims, can be an important impediment to development.

Primary supply

Primary supply is affected by such physical factors as ore grade and tonnage, location of mining and processing facilities, and availability of reserves. Each deposit is unique and affected more by some factors than others and those which are most important will vary from one deposit to the next. For example, considerations of indigenous peoples is highly important in the Goro nickel deposit in New Caledonia or the Voisey's Bay nickel deposit in Canada but are not a major concern at the Pend Oreille lead-zinc deposit in Washington State.

Crustal abundance. A review of the abundance of elements in the Earth's crust shows that metals with higher atomic number tend to be less abundant, but some of those, such as the rare earth elements, are not as scarce as precious metals, like gold, or some minor metals, like rhenium and tellurium. There seems to be a tendency for metals with higher crustal abundance to have higher production volume, which might be expected, but the critical factors in availability of valuable minerals are where and how mineralization is distributed in the crust and the depth at which mineralization occurs (McKelvey, 1972).

Deposit size and grade. Size in terms of tonnage is an important consideration in determining the feasibility of development of any deposit. While very high localized concentrations may be found, if the tonnage is not sufficient, the enormous cost of development of mining, processing, and sometimes refining facilities, especially for an underground mine, cannot be justified. At the same time, grade of ore must be sufficiently high to justify the cost of extracting the mineral commodity from its host rock. Such concentrations are increasingly difficult to find, which is why the cost of exploration is so high. For many metals used in energy- related technology applications, concentrations high enough to justify recovery of the metal either do not exist at all or are very rare. In these cases, these metals are usually recovered as byproducts of another mineral commodity more commonly found in sufficiently high concentrations, such as copper, nickel, aluminum, or zinc. In the case of tellurium, a byproduct of copper mining, its production is also inhibited by expansion in the use of leaching solvent extraction/electrowinning, and the concomitant decrease in smelting is limiting the growth of tellurium supply.

Ratio of reserves to production. Comparisons are sometimes made between ratios of world reserves to annual world production for certain metals (Strauss, 1948). The reserves in 2009 of each of the metals in the MIT Energy Initiative study – rare earths, tellurium, and cadmium − are substantial, indicating that at current rates of consumption, reserves would be sufficient for many years. In terms of rank, rare earths are highest, followed distantly by cadmium. A world ratio for tellurium could not be calculated, as U.S. production must be withheld because data are proprietary, and world production is unknown. However, world reserves are relatively high at 22,000 tons, which may be considered adequate for the scale on which tellurium is likely consumed. U.S. helium reserves are many times U.S. consumption, but world reserves are not available. Of the 29 minerals evaluated, 8 had a very high ratio (above 100) of world reserves to production in 2009, including rare earths, lithium, magnesium, platinum, aluminum, titanium, beryllium, and cobalt, whereas the remainder (21) had a ratio below 100, including some that are mined as principal products, such as copper and zinc. The latter category also includes byproduct minor metals, such as cadmium, thallium, and antimony, as well as precious metals, such as gold, so it is difficult to make a generalization about certain groups of metals having higher ratios. Also, while there does appear to be a direct proportionality between crustal abundance and reserves (McKelvey, 1972), there does not appear to be any clear relation between crustal abundance and reserves to production ratio.

Note that future discoveries are not reserves and therefore not included in these ratios. The assessment of undiscovered resources is a major challenge addressed by USGS mineral resource research.

Concentration of production and reserves. Concentration, here defined as the aggregate percentage of world production or reserves of the three leading countries, is one indicator of the vulnerability of supply to disruption, whether it be by natural disaster, political unrest or instability, conflict, or simply control of production rates or influence that governments may have over production rates. As one might expect, mine production and reserves have a similar pattern of concentration. However, the countries in which these respective measures are concentrated are not necessarily the same. For example, rare earths production is concentrated principally in China, but significant rare earths reserves are also found in the Commonwealth of Independent States, the United States, and Australia. Lithium production is concentrated in Chile, Australia, and China, whereas lithium reserves are concentrated in Chile, China, and Brazil. Cobalt production is concentrated in Congo, Canada, and Zambia, whereas cobalt reserves are concentrated in Congo, Australia, and Cuba. This is an indication of the potential for increased production through further development in countries other than the main producers. Also, the reserves are many times annual production for each of these metals, so there is easily adequate material in the ground for the foreseeable future.

Dynamics of primary supply. The tonnage and grade of a deposit are constantly changing, in theory, as price changes with market conditions. Economic (or cutoff) grade changes with costs of production and price. This is the grade (concentration) below which it is not economic to recover the metal. Rising price lowers the grade of ore that may be profitably produced, thereby expanding reserves, but it may also result in increased cost of production. As reserves are drawn down through production or as demand increases, prices eventually will rise, prompting further exploration and discovery of new deposits. Most recently, the surge in demand from China spurred exploration in many mineral commodities. In addition, over time, mining and processing technology changes will lower costs of production, making it more economic to mine lower grade deposits.

Location, depth, and mineralogy. Location of a deposit is also an important consideration. Deposits in isolated areas, such as above the Arctic Circle or high in the mountains where no infrastructure exists, are much more costly to develop, and the cost of transporting ore to processing facilities is also high. For planned open pit mines, the depth of overburden, and therefore cost of its removal, is a factor as well. However, operating costs for open pit mines are generally less than for underground mines. Mineralogy may play an important role in determining cost as well because if certain unwanted elements, such as arsenic or thorium, are present, difficulty in dealing with them, either in processing or disposal, may outweigh the benefit of extracting the more valuable metal.

Other factors. Other mining circumstances, which include whether the metal is mined as a principal product, byproduct, or coproduct, affect the production cost and, therefore, the price of metals. If the mineral produced is a principal product, production can more readily respond to price changes. Byproduct metal production depends on the principal product's market conditions; therefore, these metals can be subject to more unpredictable price swings. As noted earlier, the type of ore (sulfide, oxide, etc.) also affects the cost of production and therefore the price of metal.

Secondary supply

Recycling can contribute significantly to the production of a metal. Industry has integrated the recycling of cadmium, cobalt, and nickel into process streams to the degree that they are now essential feed materials.

The USGS has conducted a series of studies on the recycling flow of metals (Sibley, 2004). Quantities were developed for such measures as consumption, imports, exports, stocks, and unrecovered scrap. These measures have varying levels of uncertainty, and knowing this can be important for anyone consulting these numbers. Reported numbers, such as imports and exports or old scrap consumption, have the least uncertainty. Derivative numbers, such as recycling efficiency, particularly those involving estimated numbers, such as old scrap generated, are more uncertain. Old scrap generated is probably the most difficult component of secondary supply to estimate because it requires estimation of lifetimes of products so that the amounts becoming obsolete can be estimated.

The USGS defines recycling rate as the quantity of old and new scrap recycled as a percent of apparent supply. The difference between the recycling rate and 100% is the primary supply. The recycling rate for cadmium, the only energy-related mineral commodity cited by the study group for which a USGS recycling flow study was done, was estimated to be about 30%.

Efficiency is old scrap recycled as a percent of old scrap available to be recycled, and the difference between that and 100% is unrecovered scrap. In the case of cadmium, efficiency was also estimated to be about 15%, indicating significant potential to recover more material from scrap.

Recycling rate is a function of apparent supply, and efficiency is a function of old scrap generated. Old scrap consumed is compared with each, respectively, to determine recycling rate and recycling efficiency. However, there is no apparent correlation between recycling rate and recycling efficiency. There is an obvious clustering of recycling rates in the 20 to 40 percent range, whereas efficiencies range from 5% to 95%. Recycling rate and recycling efficiency are believed to change very slowly over time, so theses measures continue to be useful in that they can be applied after the year of a particular study.

As an example of several mineral commodities studied, iron and steel and manganese recycling rates are similar because they are used together. The chromium recycling rate is relatively low because of its abundance in primary form and low cost of primary production. Recycling efficiency for iron and steel is the same as that for manganese but high for chromium because of the high rate of recovery of stainless steel scrap. New to old scrap ratios are similar for these mineral commodities at about 35:65.

If the individual metal recycling industries are considered to be independent, overall metal recycling rate and efficiency calculated by averaging percentages rather than on a total weight basis, show that overall efficiency and recycling rate are comparatively low, reflecting the lesser developed recycling infrastructure of the lower volume mineral commodities, such as cobalt, molybdenum, and tantalum, uses for which tend to be more dissipative. Exceptions are the high efficiencies for high value metals, such as platinum and gold, but recycling rates are relatively low for these metals because of the abundance of primary material. On a total contained weight basis, the overall metal recycling rate and efficiency naturally gravitate toward those of steel. Factors affecting recycling efficiency include cost of collection, cost of processing, volume of material available, and price of processed scrap.

SELECTED ENERGY RELATED MINERAL COMMODITIES

Cadmium

Sphalerite (zinc sulfide), the most economically significant zinc ore mineral, commonly contains small amounts of other elements, including cadmium, indium, and germanium. Cadmium is present in zinc ores at a content that can vary between 0.25% and 0.5%. It was estimated that about 80% of the global cadmium supply is recovered as a byproduct from the processing of zinc ores and zinc-bearing lead ores. The remainder of the cadmium metal supply comes from the recycling of spent NiCd batteries. There are only a handful of facilities that recover cadmium from NiCd batteries (Tolcin, 2010).

During the past 10 years, cadmium production has moved from Western Europe to Asia, specifically China. The global production profile for cadmium is now dominated by Asia, with more than 50% of cadmium production originating from China, the Republic of Korea, and Japan. Other significant cadmium-producing regions include North America and Central Eurasia. NiCd battery production is the leading end use of cadmium, accounting for most of the global cadmium consumption. Other end uses of cadmium include pigments, anticorrosive coatings, polyvinylchloride stabilizers, alloys, and semiconductor compounds for solar cells. The percentage of cadmium consumed globally for NiCd battery production has increased during the past decade, as the percentages for the other traditional end uses of cadmium—specifically, coatings, pigments, and stabilizers—have decreased because of environmental and health concerns. Most of the NiCds on the market are small, relatively inexpensive, consumer cells that are used in portable devices—commonly power tools, in which battery cost is more of an issue. Large, industrial NiCd batteries are used for start-up or emergency backup power, particularly for locomotive and aircraft electrical systems (Tolcin, 2009).

Concern about cadmium's toxicity has spurred various legislative efforts, especially in the European Union, to restrict the use of cadmium in most of its end-use applications. If recent legislation involving cadmium dramatically reduces its long-term demand, a situation could arise (such has been seen with mercury) where an accumulating oversupply of byproduct cadmium will need to be permanently stockpiled (Tolcin, 2010). However, there are several new market opportunities for NiCd batteries, particularly in industrial applications – NiCd batteries can be used as energy storage devices for solar arrays and wind farms because of their exceptional stability under a wide range of temperatures and ability to withstand repeated cycling. During the past decade, U.S. and Japanese consumption of cadmium metal declined, while China's consumption increased dramatically. Therefore, NiCd battery manufacturers relocated their manufacturing facilities to China, which is also the leading cadmium producer. Cadmium metal consumption during this time period has generally declined, which may be attributed to decreased use of cadmium in coatings, pigments, and stabilizers and the increased substitution of NiCd batteries in certain consumer electronics with other rechargeable battery chemistries. NiCd's have been largely replaced by Li-ion batteries in cellular phones and laptops, and an increasing quantity of Li-ion batteries is being used in power drills (World Bureau of Metal Statistics, 2009).

Lithium

Subsurface brines are the dominant raw material used to produce lithium carbonate–the chemical which is used in Li-ion battery manufacturing. This is because the production costs of processing brine into lithium carbonate are lower than those of mining and processing of lithium ores. The two brine operations in Chile dominate the global market supply of lithium carbonate. Lithium concentrates and brine are produced in only a few countries. Chile was the leading lithium chemical producer in the world in 2009. Argentina, China, and the United States were also major producers. Australia, Portugal, and Zimbabwe were major producers of lithium concentrates from hard rock sources (Jaskula, 2010).

Most of the minerals mined from lithium ore deposits are used directly in ceramics and glass applications, rather than processed into lithium carbonate or other lithium compounds. However, some new lithium projects in Western Australia plan to produce hard rock (spodumene) and process it to lithium carbonate. Lithium's leading end use is in ceramics and glass (30%), followed by batteries, mainly lithium-ion (Li-ion), at 21%. These batteries represent more than 70% of the total rechargeable battery market worldwide (Rockwood Holdings, 2008). Rechargeable lithium batteries are found in the majority of cellular telephones and laptop computers, but lithium batteries account for less than a quarter of total lithium consumption. In another 10 years, batteries are expected to account for about 40% of total lithium consumption (Anderson, 2009; deSolminihac, 2010; Rockwood Holdings, 2008).

Despite the approximate 15% drop in lithium consumption in 2009 because of the economic recession, global consumption of lithium is trending upward, which is a reflection of increased Li-battery manufacturing overseas, but consumption is declining in the United States (Baylis, 2010).

According to Sociedad Quimica y Minera de Chile S.A.'s latest view of projected global lithium carbonate consumption, use of Li batteries for vehicles is expected to expand. Total lithium carbonate consumption is expected to reach 190,000 metric tons by 2020. Lithium carbonate for vehicles is expected to grow at 40% compound annual growth rate from 2010-2020, reaching 40,000 metric tons by 2020 (de Solminihac, 2010; Yaksic and Tilton, 2009).

Rare earths

Some rare earths are more abundant than many industrial metals, but the REEs are much less likely to be found concentrated in exploitable ore deposits. Consequently, most of the world's supply comes from only a few sources.

Bastnasite deposits in China and the United States contain most of the global REE resources, while monazite deposits located in nine countries (Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the United States) contain the rest. China is now the dominant producer of rare earth elements, including production from clay deposits that are enriched in heavy rare earth elements. In 2009, global mine production of rare earths was estimated to have totaled 124,000 metric tons. China accounted for about 97% of this production. The remaining 3% was contributed by India, Brazil, and Malaysia (Hedrick, 2010b).

Supply is expected to increase with increased development of deposits in China and several outside of China. The rare earth separation plant at Mountain Pass, CA, resumed operations in 2007 and continues to operate in 2010. Removal of overburden at the Mt. Weld REE deposit in Australia was completed in June 2008, and in late 2009, the company was fully financed. Opening of the mine and concentrator at Mt. Weld and the advanced materials plant in Kuantan, Malaysia, is planned for early 2011 (Metal Pages, 2010). Economic assessments continued at other REE deposits in Australia, Canada, Malawi, and Vietnam.

Consumption data for REEs are not available. High-tech and environmental applications using REEs have grown sharply in number and diversity during the past four decades. As many of these applications are highly specific—meaning REE substitutes are inferior or unknown—interest in the REEs has increased recently (Hedrick, 2010a).

Rare earth use in automotive pollution control catalysts, lasers, light emitting diodes, permanent magnets, and rechargeable batteries is expected to continue to increase as consumption for conventional and hybrid automobiles, computers, electronics, and portable equipment increases.

Future increases in consumption of REEs are expected in rechargeable NiMH batteries, especially those used in hybrid vehicles. The amount of REE consumed for these batteries was forecast to increase from 10,000 metric tons to 20,000 metric tons rare earth oxides by 2012. (A typical hybrid electric vehicle NiMH battery contains 10 to 12 kilograms of REEs.) (Kingsworth, 2008).

SUMMARY

In summary, in general for metals:

- **Reserves will increase with higher prices and greater exploration, but significant increases in supply take 5 to 15 years. This is the lead time necessary for re-starts, expansions, or new operations.**
- **Short-term supply shortfalls are possible because of inadequate mine and plant production capacity.**

- **There is significant potential for increased recovery from scrap; the significance of mineral scrap recovery for total supply differs for many mineral commodities.**
- **World supply of most metals used in energy technology applications is adequate for the foreseeable future (assuming current rates of consumption). Until additional planned production comes on stream, there could be problems with rare earth element supply.**

Acknowledgments and USGS sources of information

Under the Mineral Resources Program (MRP) of the USGS, minerals information is collected domestically from producers and consumers and internationally from a variety of sources in foreign countries. All USGS minerals information publications are available on the internet and can be downloaded at the Web address http://minerals.usgs.gov/minerals. The types of information that are collected and disseminated include production, consumption, stocks, trade, prices, mineral commodity issues, and mineral industry developments. The information is used in determining apparent consumption, import reliance, and price trends, as well as in materials flow studies, among other applications. In addition to the several cited USGS reports, significant contributions came directly from USGS minerals information staff. Mineral resource research and assessment in the USGS MRP provides information for land planners and decision makers about where mineral commodities are known and suspected in the Earth's crust and about economic and environmental consequences of the presence of those commodities. USGS mineral-resource activities also include the development of national-scale geologic, geochemical, geophysical, and mineral resource databases and the migration of existing databases to standard models and formats that are available to both internal and external users.

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Presentation, Jung-Chan Bae,
Strategies and Perspectives for Securing Rare Metals in Korea


Strategies and Perspectives for Securing Rare metals in KOREA
2010. 04. 29
APS Workshop, MIT Boston
Jung-Chan Bae
Production Technology R&D Division
Korea Institute of Industrial Technology (KITECH)


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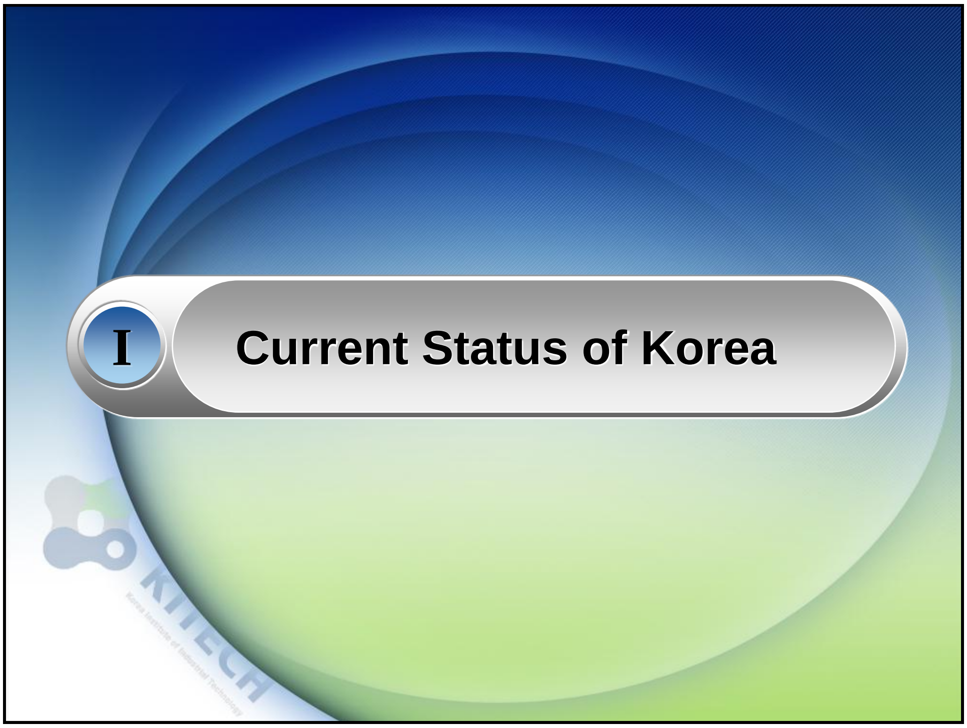
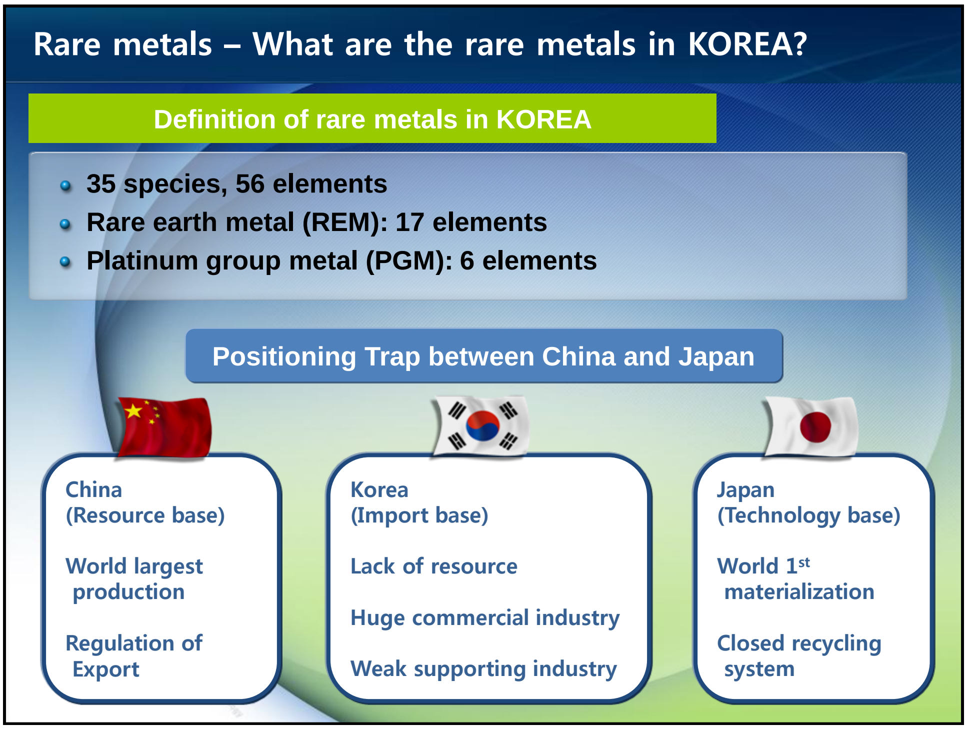
II
Strategies for securing Rare metals


I
Current Status of Korea


Rare metals – What are the rare metals in KOREA?
Definition of rare metals in KOREA
35 species, 56 elements
Rare earth metal (REM): 17 elements
Platinum group metal (PGM): 6 elements
Positioning Trap between China and Japan
China
(Resource base)
World largest production
Regulation of Export
Korea
(Import base)
Lack of resource
Huge commercial industry
Weak supporting industry
Japan
(Technology base)
World 1st materialization
Closed recycling system

Rare metals – Demand & Supply Characteristics

Relative concept depends on countries or era

Rarity → Unstable supply → Unstable price

Rarity

Element	Resource Rarity*
PGM	23,000,000
In	3,800,000
Se	1,200,000
Cd	250,000
Bi	240,000
Sb	180,000
Ta	66,000
W	33,000
Sn	29,000
Ge	17,000

* Exhaustion rate of steel =1

Unstable supply

Element	1st Product Country	Share
REE	China	97.1
Nb	Brazil	89.8
W	China	86.5
Sb	China	81.6
Ta	Australia	62
B	Turkey	58.7
PGM	South Africa	58.6
Si	China	57.7
In	China	54.8
Bi	China	52.5

Unstable price

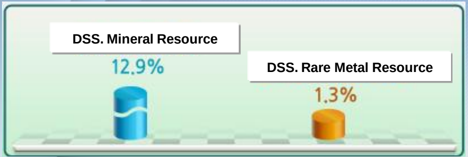
Element	$/ton (2002yr)	$/ton (2007yr)	Price Variation (%)
Se	8267	72222	774
Mo	8840	70260	695
In	87140	680800	681
Ni	6772	37181	449
Bi	6658	31437	372
W	5400	24826	360
V	9662	43295	348
Co	15719	64440	310
Cr	717	2761	285
Ti	5980	22530	277

[Global provision] Intensifying exhausting of resource and instability of supply
[Domestic needs] Growth of Rare metals consumption industry

Current state of KOREA (Industry)

Natural Resource

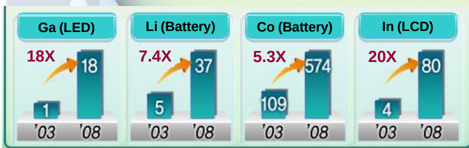
- Low degree of Self Sufficiency (DSS)



Materials

- Rapid increasing of Rare-metal Materials Import

Amount of Rare metallic materials import ($US Mil.)



Industrial Structure

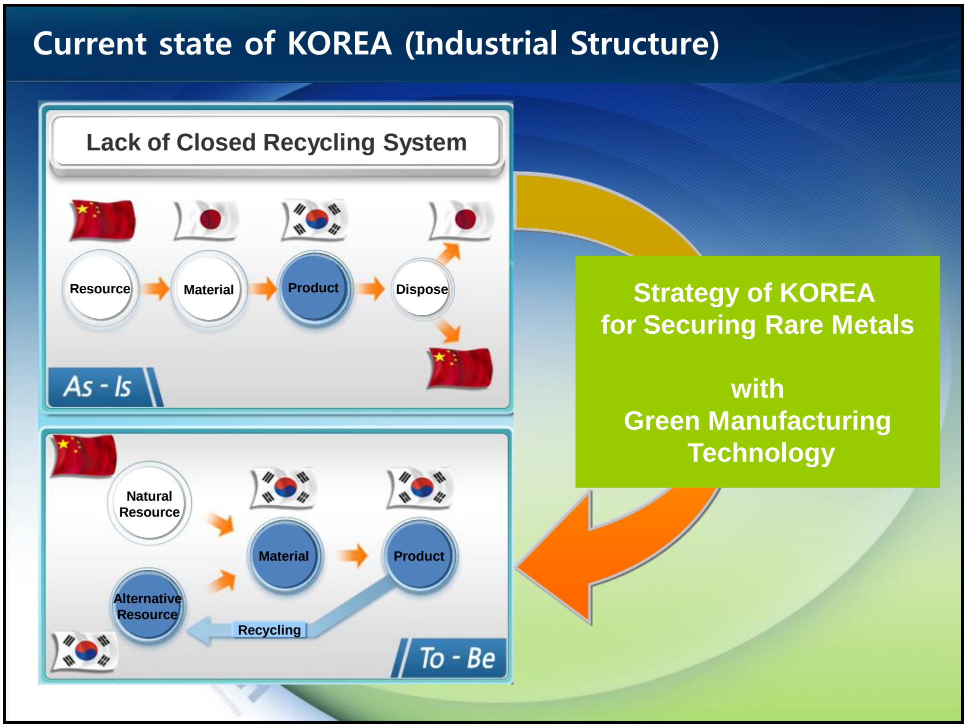
- Weak Rare-metal Production Industrial Base

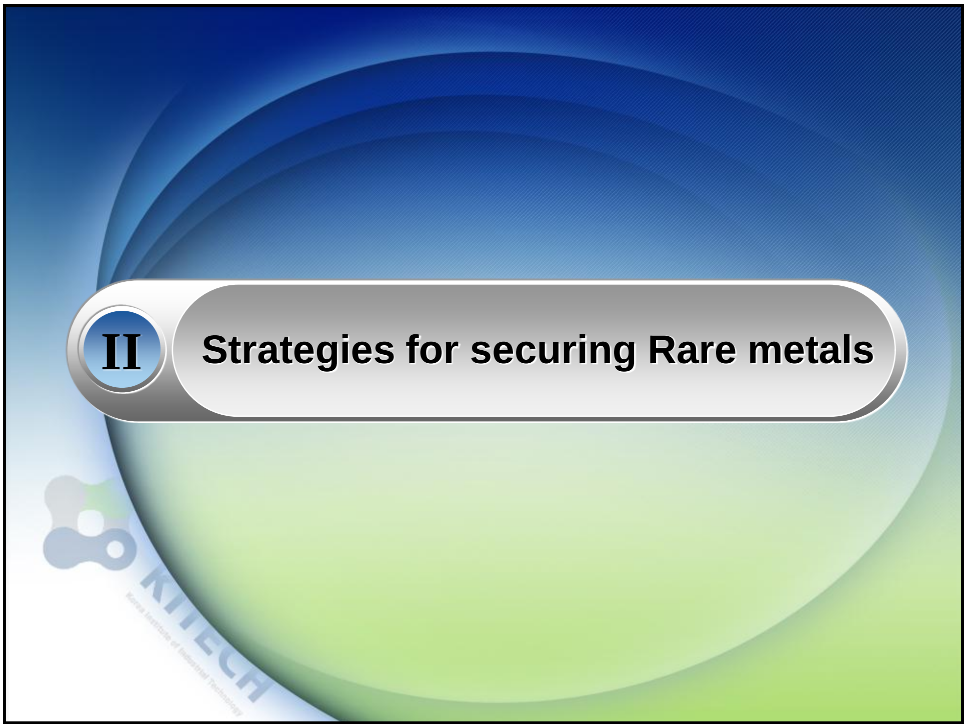
Resource import : Material import = 1:9

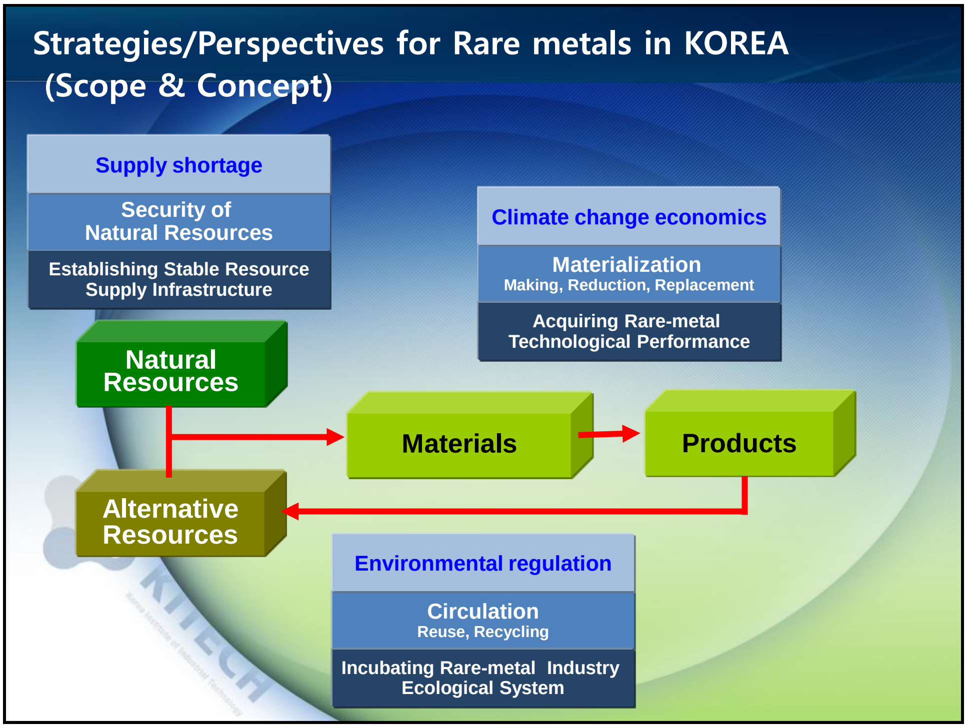
Current state of KOREA (Technology)

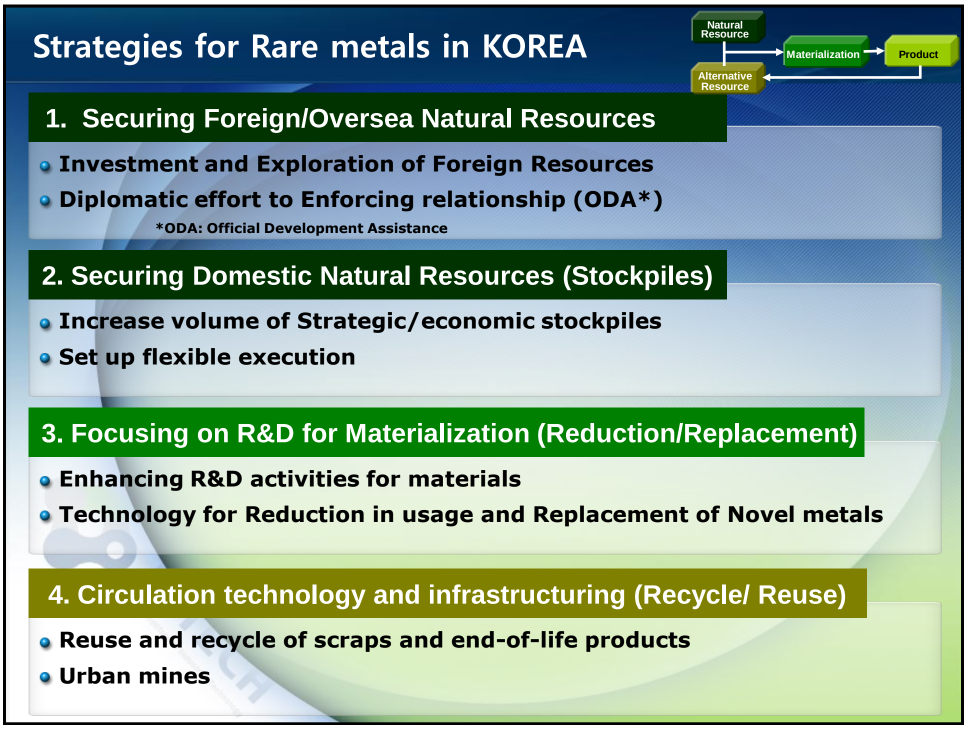
Weak point of current states and key-point for sustainability

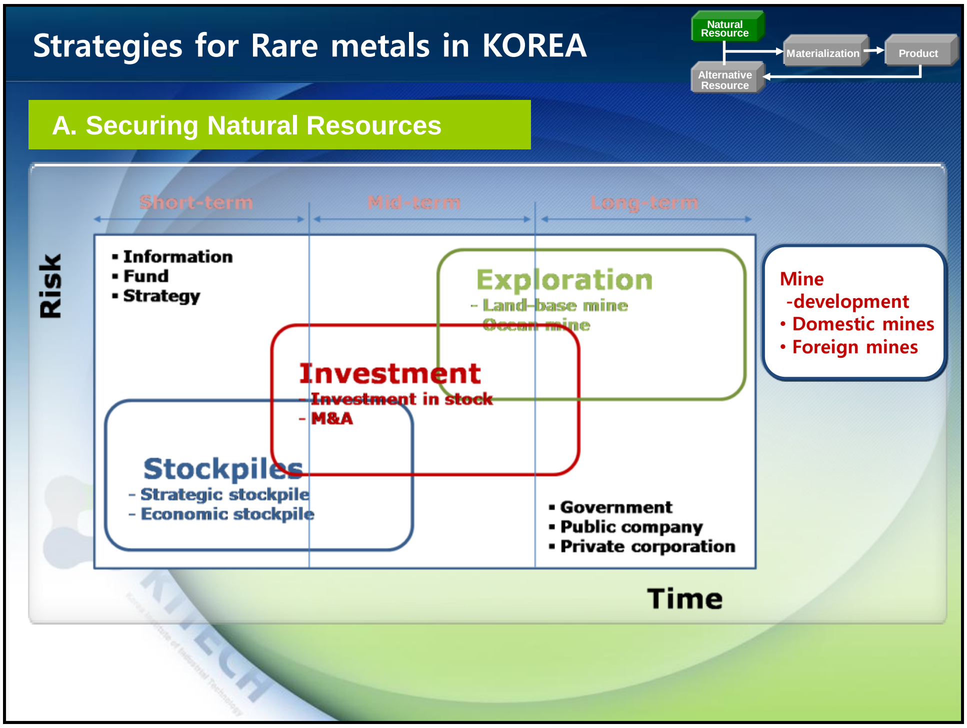
Step	Resources	Materials	Products	Recycle
Current States	Negligible	Weak-point in value chain	Competitive - Semi-conductor - Display - Automotives - IT products…	Negligible (disposal or export)
Potential Competitive Power	Ocean mines N. Korea Urban mines	Enhancing - Remelting - Refining - Eco-making - Recycling Tech. transfer	Competitive - Renewable energy - Semi-conductor - Displays - Green car - Mobile devices…	Scraps End-of-life products


Current state of KOREA (Industrial Structure)
Lack of Closed Recycling System
Resource
Material
Product
Dispose
As - Is
Natural Resource
Alternative Resource
Material
Product
Recycling
To - Be
Strategy of KOREA for Securing Rare Metals
with
Green Manufacturing Technology


II
Strategies for securing Rare metals

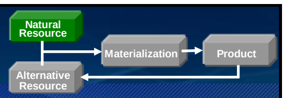

Strategies/Perspectives for Rare metals in KOREA
(Scope & Concept)
Supply shortage
Security of Natural Resources
Establishing Stable Resource Supply Infrastructure
Climate change economics
Materialization
Making, Reduction, Replacement
Acquiring Rare-metal Technological Performance
Natural Resources
Materials
Products
Alternative Resources
Environmental regulation
Circulation
Reuse, Recycling
Incubating Rare-metal Industry Ecological System


Strategies for Rare metals in KOREA
Natural Resource
Materialization
Product
Alternative Resource
1. Securing Foreign/Oversea Natural Resources
Investment and Exploration of Foreign Resources
Diplomatic effort to Enforcing relationship (ODA*)
*ODA: Official Development Assistance
2. Securing Domestic Natural Resources (Stockpiles)
Increase volume of Strategic/economic stockpiles
Set up flexible execution
3. Focusing on R&D for Materialization (Reduction/Replacement)
Enhancing R&D activities for materials
Technology for Reduction in usage and Replacement of Novel metals
4. Circulation technology and infrastructuring (Recycle/ Reuse)
Reuse and recycle of scraps and end-of-life products
Urban mines


Strategies for Rare metals in KOREA
Natural Resource
Materialization
Product
Alternative Resource
A. Securing Natural Resources
Short-term
Mid-term
Long-term
Risk
▪ Information
▪ Fund
▪ Strategy
Exploration
- Land-base mine
Ocean mine
Investment
- Investment in stock
- M&A
Stockpiles
- Strategic stockpile
- Economic stockpile
▪ Government
▪ Public company
▪ Private corporation
Mine
-development
• Domestic mines
• Foreign mines
Time


Strategies for Rare metals in KOREA
Natural Resource
Materialization
Product
Alternative Resource
1. Securing Overseas Natural Resources
Enforcing Resource Politics
Dispatching investigation team : South Africa, Zimbabwe, Madagascar
Establishing Korea-China collaboration : KCMIC (Korea-China Material Industry Committee)
Increasing Foreign Mine Development
Prior Investigation of 2 Minerals : Li (Chile, Bolivia), RE
Modifying Regime/Law to Enhancing Support System
Endorsing Incentives to Develop Foreign Mineral Resources for CSEs

Strategies for Rare metals in KOREA



2. Securing Domestic Natural Resources

Investigating Stockpiles & Reserves

- Accurate Investigation & Estimating Economical Viability

Domestic Mine Development

3. Increasing Volume & Species of Domestic Stockpiles

Government Driving Plan

- 60 days Consumption amount/ Each element for 21 Metals
- Supplying Governmental Stockpile System for Industries

Strategies for Rare metals in KOREA

B. Enhancing R&D activities for Materialization

1. Designation Strategic Rare metal & Essential Core Technology

Starting from R&D programs

- Strategic Rare metals (~2009): 11 Elements, Enlarge to 20 Elements
- Essential Core Technology : 40 Technologies, Develop R&D Programs

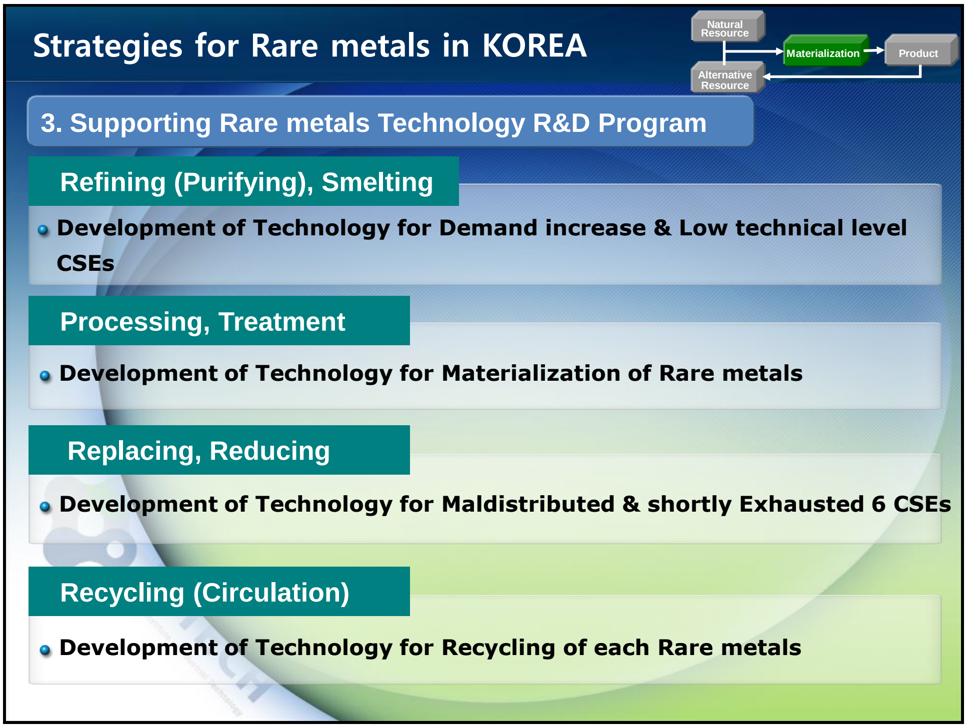
2. Establishing Roadmap in Each Sections

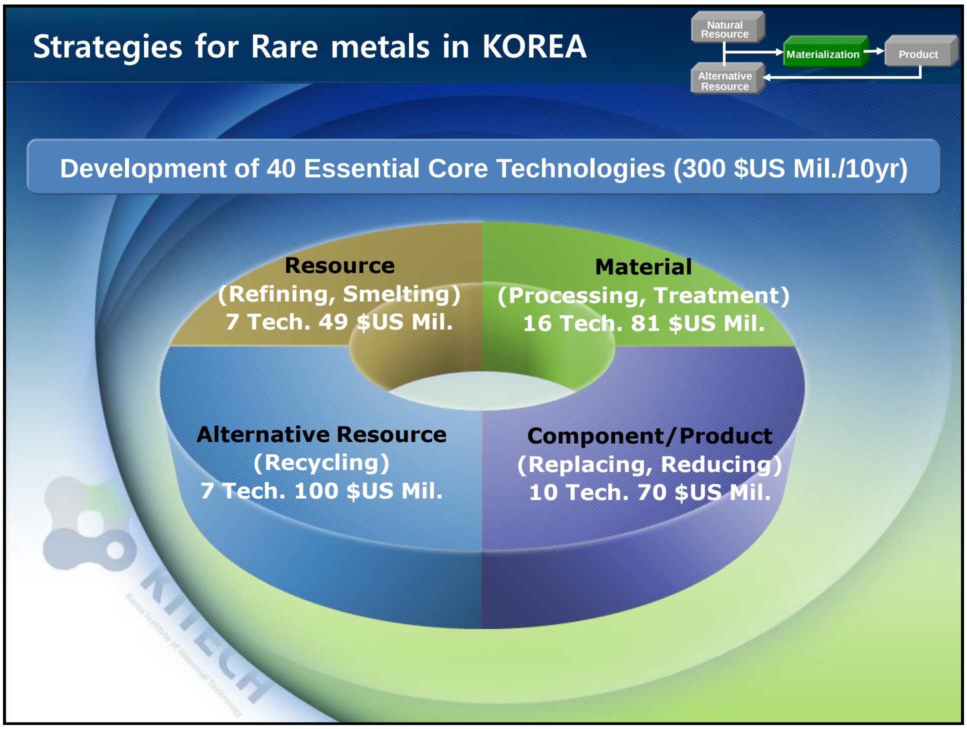
Prior Commercialization

- R&D collaboration between Demander & Supplier (In, PGM)

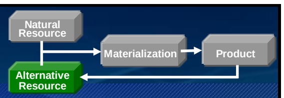
Cutting edge Industry

- Government Leading R&D : Li, RE, Ti


Strategies for Rare metals in KOREA
Natural Resource
Materialization
Product
Alternative Resource
3. Supporting Rare metals Technology R&D Program
Refining (Purifying), Smelting
Development of Technology for Demand increase & Low technical level CSEs
Processing, Treatment
Development of Technology for Materialization of Rare metals
Replacing, Reducing
Development of Technology for Maldistributed & shortly Exhausted 6 CSEs
Recycling (Circulation)
Development of Technology for Recycling of each Rare metals


Strategies for Rare metals in KOREA
Natural Resource
Materialization
Product
Alternative Resource
Development of 40 Essential Core Technologies (300 $US Mil./10yr)
Resource
(Refining, Smelting)
7 Tech. 49 $US Mil.
Material
(Processing, Treatment)
16 Tech. 81 $US Mil.
Alternative Resource
(Recycling)
7 Tech. 100 $US Mil.
Component/Product
(Replacing, Reducing)
10 Tech. 70 $US Mil.

Strategies for Rare metals in KOREA



C. Circulation for Alternative Resources

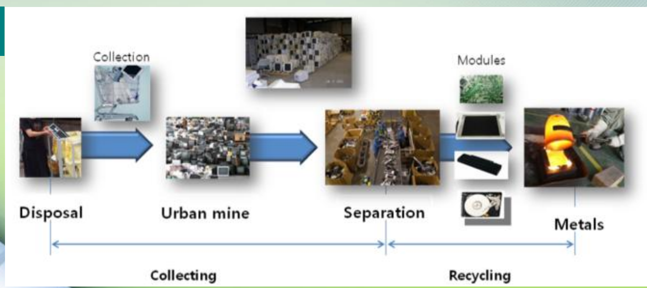
Goal of Circulation

- **Increasing national efficiency of materials utilization**

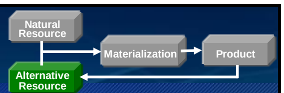
Target of Circulation

- **Recycling of scraps during manufacturing**
- **Reuse and recycling of end-of-life products (e-wastes)**

Urban Mining



Strategies for Rare metals in KOREA



Activating Circulation of Rare metals

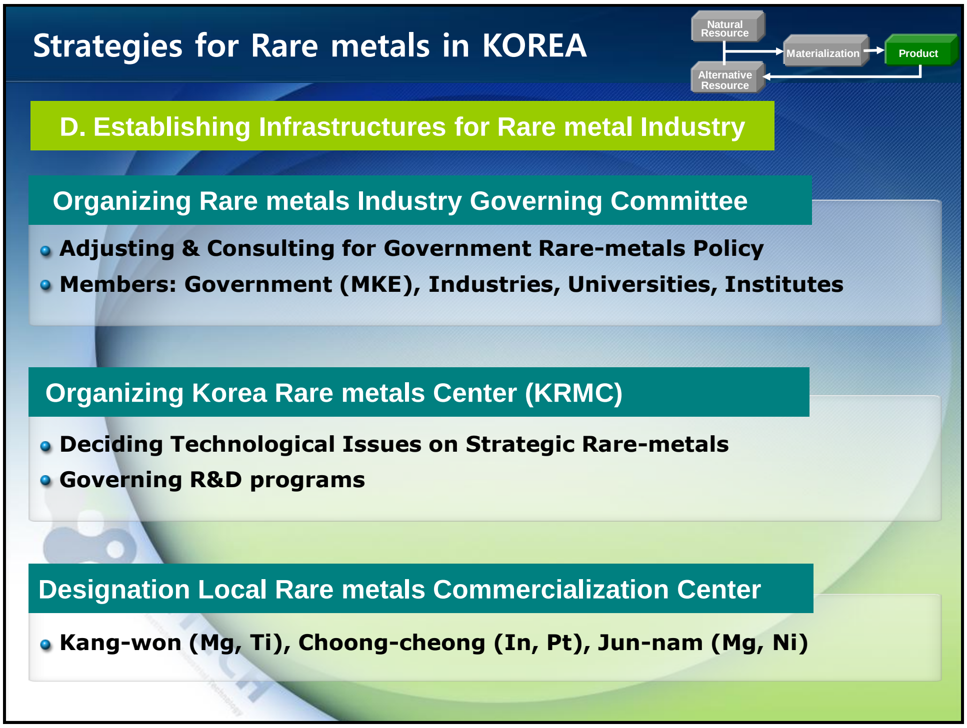
Regulating Recycling System

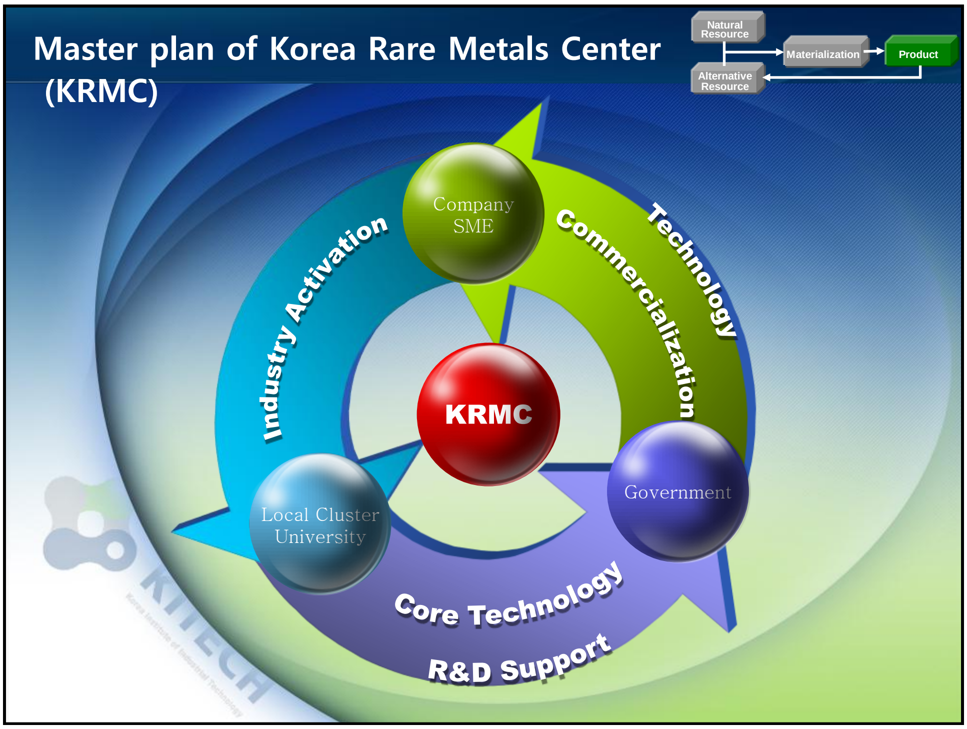
- **Electronic Product, Automobile, Byproduct**

Increasing Collect Efficiency

Introducing Content Indication System

- **"Rare metal Indication System" for the 6 CSEs of IT product :**
  Cell phone, Digital camera, MP3, Navigation


Strategies for Rare metals in KOREA
Natural Resource
Materialization
Product
Alternative Resource
D. Establishing Infrastructures for Rare metal Industry
Organizing Rare metals Industry Governing Committee
Adjusting & Consulting for Government Rare-metals Policy
Members: Government (MKE), Industries, Universities, Institutes
Organizing Korea Rare metals Center (KRMC)
Deciding Technological Issues on Strategic Rare-metals
Governing R&D programs
Designation Local Rare metals Commercialization Center
Kang-won (Mg, Ti), Choong-cheong (In, Pt), Jun-nam (Mg, Ni)


Master plan of Korea Rare Metals Center (KRMC)
Natural Resource
Materialization
Product
Alternative Resource
Company SME
Industry Activation
Technology Commercialization
KRMC
Government
Local Cluster University
Core Technology R&D Support


Strategies for Rare metals in KOREA
Natural Resource
Materialization
Product
Alternative Resource
1. Incubating Rare metals Specialized Company
Support Investment Fund & Tax Exemption
Enlarging Government–Industry Investment
KORES will invest 820 $US Mil. until 2013 to found Rare metals Specialized companies
Ex) Kwang-Yang FerroAlloy Co.(Mo) was founded 2007 by joint venture of KORES(GOV.) and KTC
2. Establishing Infrastructure for Rare metal Industry
Setting up Materials Flow & Statistical DB
Training Rare metal Specialist
Establishing International Collaboration


Realization of Strong Power Nation in Rare metal Industry
(Resource-Industry-Chain of Value)
- RICH KOREA 1040 -
Deg. of Self Sufficiency
DSS (11 Strategic Elements)
12%
60%
80%
2009
2015
2018
Guarantee Core Tech.
Core Tech.
Technical Level
No.2
60%
25
85%
40
95%
2009
2015
2018
Found Special Company
No. of Company
25
50
100
2009
2015
2018
Securing Resources
Developing R&D
Establishing Infrastructure

White Paper, Dayan Anderson,
A Communications and Outreach Perspective

APS-MITEI-MRS Workshop Critical Elements for New Energy Technologies

A Communications & Outreach Perspective

Dayan J. Anderson[1]

Although policy makers have been identified as the primary audience for the "Critical Elements for New Energy Technologies" study, the **need** for the policy recommendations that emerge must also be effectively communicated to the constituents the policy makers serve. Ultimately, these constituents will be involved, directly or indirectly, in many if not most of the decisions impacting the final feasibility of new energy technologies. Whether it be decisions to site a specific energy project, approval to develop the mineral resources required to manufacture new energy technologies, or acceptance of taxes or other policy incentives to encourage post-consumer recycling, communities and stakeholders need to understand, or at least have a broader appreciation for, the complexity of these issues and how each decision integrates into the larger solution.

There is societal "confusion" about mineral supply[2] and recyclability that needs to be corrected before society can make informed decisions about the materials it will use to sustainably meet the needs of a growing population. The comments and suggestions that follow are focused on raising society's general awareness, appreciation and understanding of materials, and the role materials will play in society's transition to sustainability.

The ability to effectively communicate complex issues to policy makers and the general public is limited by the attention-span, as well as the vocabulary, of the listener. Careful attention must be paid to word selection, and any use of technical lexicon must be accompanied with clear and consistent definitions. One approach to communicating technical content is to first frame complex issues using terminology with which the audience may have more familiarity. A suggested approach to framing the conservation about raw material supply and sustainability is offered below.

Over the past two decades, footprint metrics and accounting methodologies have emerged that represent generalized proxies of how individual, organizational or national decisions impact land, air and water as illustrated in Figure 1. Technologies to meet human needs and to lower these footprints will require diverse material sets, and production of these materials depends on a complex combination of animal, plant, mineral and energy inputs, as illustrated in Figure 2. Each footprint is linked to jobs and livelihoods in a global economy as shown in Figure 3, and although not graphically depicted, there are of course complex social impacts (both positive and negative) surrounding the production, use and disposal of these materials. Placing a solitary focus on any single footprint or emphasizing sub-sets of these footprints at the expense of others will not lead to the 'best' decisions for sustainability. Rather, increased societal understanding of the relationships *between* these footprints (i.e., how they interact, overlap and influence each other) and furthermore, an understanding of how our choices <u>reinforce</u>, <u>distort</u> or <u>sever</u> these relationships is required.

Using a simple teeter-totter to depict the concept of sustainability as shown in Figure 4, society's overall environmental footprints are currently large and "heavy" and the basic needs of most of the world's population are not being met. In other words, current patterns of consumption and production do not represent a stable system. Figure 5 suggests how society might bring this system into an acceptable, and more sustainable balance; namely, by determining how it can best **leverage** technology (and the materials sets they will require) to minimize environmental impacts

[1] President, Mineral Footprint Network (danderson@mineralfootprint.org ● PO Box 5080 Sugarloaf CA, 92386 ● 909.547.0780) Additional input on market dynamics and mineral availability provided by Dr. Deborah J. Shields, Department of Economics at Colorado State University

[2] The distinction between "reserves" and "resources" does not appear to be well-understood by disciplines external to the extractive industries, as well as civil society in general.

and raise the well-being of a growing population. In short, materials produced in a socially and environmentally responsible manner act as the **fulcrum** for sustainability. However, with so many competing uses for minerals, metals and materials to meet its needs, how will society find the optimal solution? First of all, society cannot move the fulcrum to its optimal position without socially and environmentally acceptable engineering advancements. Likewise, these engineering advancements and technologies will not be affordable and feasible without reliable information about the complete mineral and material cycle. The information that society will need to make intelligent choices, from researchers and engineers, to investors and manufacturers, to consumers and policy makers is dynamic and needs constant monitoring and attention. Minerals, metals and materials information must be continually collected, managed, coordinated and disseminated as public domain data so all stakeholders can make informed decisions.

Figure 1:
Environmental Footprints

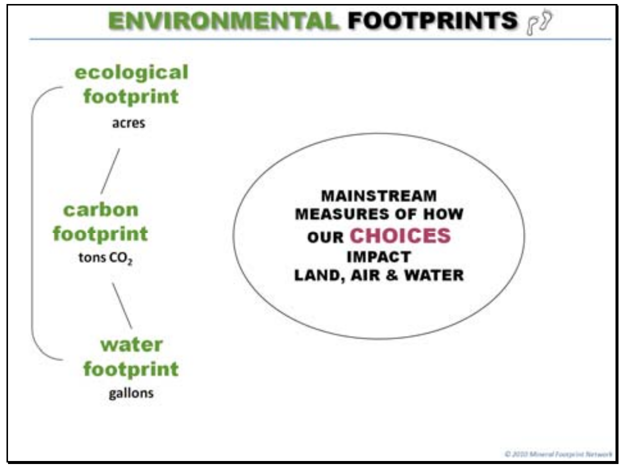


Figure 2:
Material Footprints

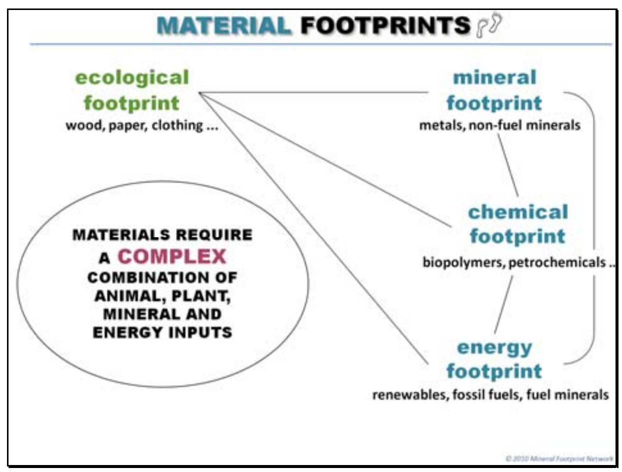


Figure 3:
Socioeconomic Footprints

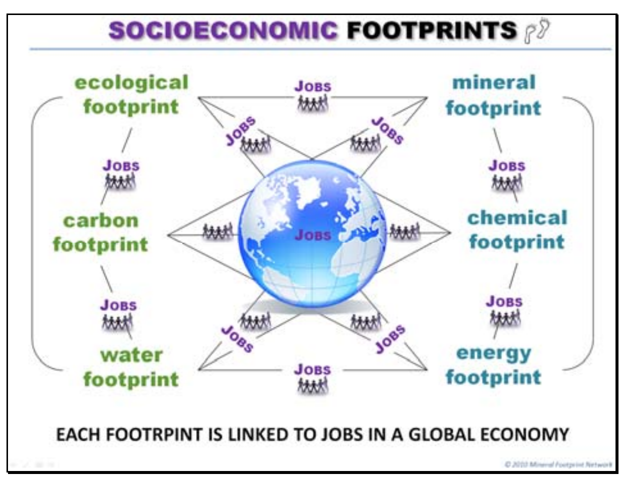


Figure 4: Current Patterns of Production and Use of Materials

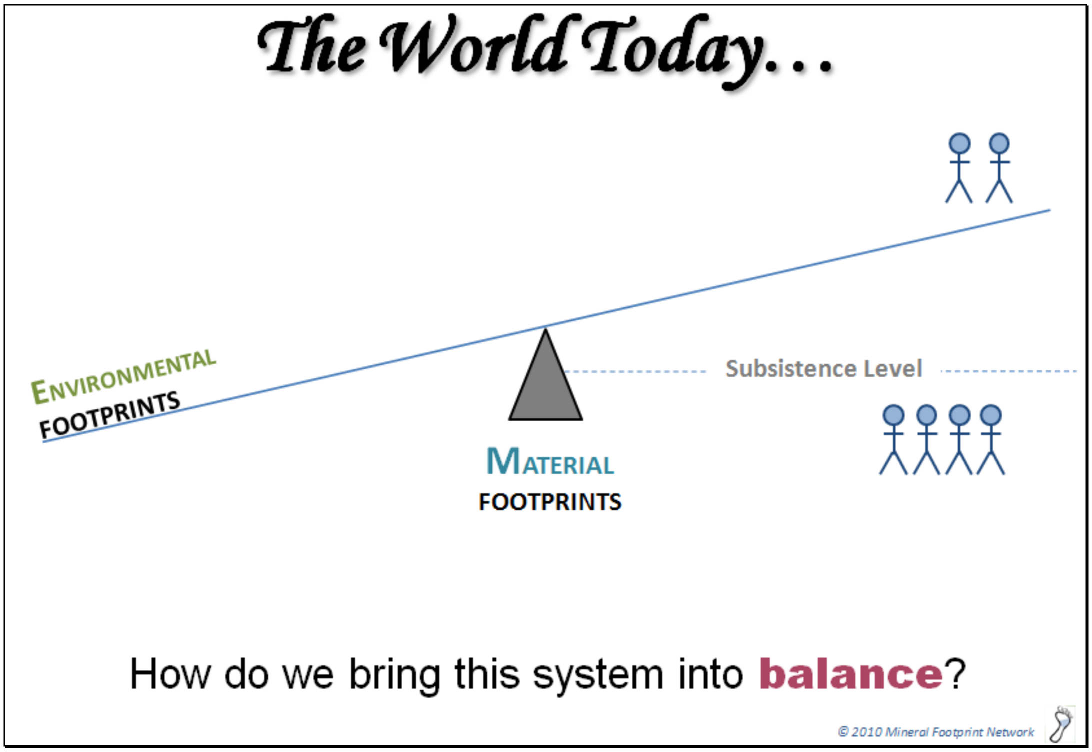
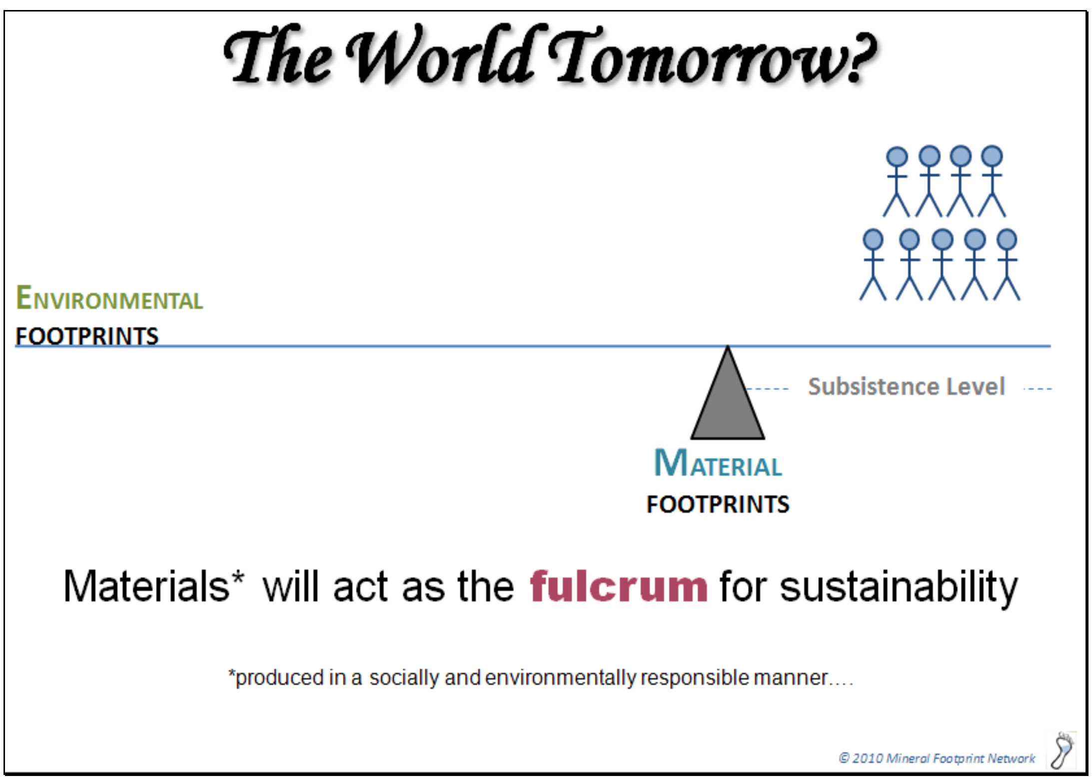


Figure 5: Sustainable Production and Use of Materials



Each of the case studies presented during the workshop identified various issues, market dynamics and characteristics that are common to most mineral resources. These messages collectively serve to communicate many (*but not all*) of the complexities of a global raw material supply. These issues have been grouped into key themes that must be communicated to raise society's understanding of the material footprints required to meet the needs of both present and future generations (see Table 1).

Table 1: Key Themes Underpinning the Complexity of a Sustainable Raw Material Supply

Themes	Comments
Variability & Uncertainty (Do we really know where "the limits" are?)	Not all deposits are 'equal' and our understanding of the quality and potential occurrences of these deposits vary by commodity and type. There is an important difference between a '*resource*' and a '*reserve*' and it needs to be made clear that we know a great deal about some minerals, but not all. There is still much about the sub-surface we do not know. The potential to recapture material once defined as sub-economic by previous generations must not be overlooked. *If we invest in R&D for new exploration, mining and mineral processing technologies* we have the potential to make more mineral resources available to society.
One-Size-Does-NOT-Fit-All	There are some "readily available" substitutes for some end-uses of a given element, while other applications rely on specific properties of certain elements and minerals for which there is (as of yet) no known alternatives. *Some* technologies and conservation measures can be implemented by *some* end-users, leaving resources available for other competing uses but this is not always the case.
Why Timely Information Matters	Changes in price affect different producers and end-users differently. Price volatility can be fueled by speculation, among other reasons. Speculation thrives on the absence of information, the proliferation of misinformation or dated information, as well as information taken out of context. This underscores the need for a transparent system of timely data collection, management and dissemination of information to the public.
We Need a More Complete Picture	The amount of public domain information on resources, reserves, recycling rates and other aspects/variables of the mineral life cycle is not complete. It is fragmented and in some cases, limited only to information in the United States.
There are 5 Dimensions of Mineral Availability	It needs to be made very clear that the mineral and energy 'reserves' available to the immediate market is a very time sensitive and ever-changing number that is dependent on many factors. For example, an individual firm's decision to invest in the delineation of additional reserves at any given point in time may be influenced by the availability of capital, tax implications, land tenure, etc. Furthermore, there are 5 sets of questions (See Table 2) that must be continually asked to quantify the mineral resources available to society at any given point in time.
There are 4 Dimensions of Recyclability	There are 4 dimensions of availability for secondary resources (post-consumer scrap) as shown in Table 3. The quantity and quality of recycled inputs is "the result of many decisions, made by businesses, individuals, and governments over a very long period of time."[3] The recyclability or potential for re-use of any mineral, metal or material is also a function of the end-use application.
Timing	Timing is a key issue for both primary production and secondary production. It can take 10-15 years or longer to bring a new discovery into production and the length of this cycle varies by political jurisdiction. The availability of old scrap relies on assumptions for the lifetimes of products which can be difficult to estimate. The dynamics between primary (virgin ore) and secondary (old scrap) supply is complicated and the question of whether or not to recycle should be re-framed to more effectively communicate this dynamic. In other words, it is perhaps more important for society to discuss *when* it is best to use recycled inputs and to identify measures taken today that will allow for the appropriate response at the proper time in the future. For example, many critical elements are produced as co-products or by-products of other metals and are consequently influenced by the prices of the principal commodity being developed. Other elements currently reporting to waste-streams of existing processes could be recovered as by-products with additional investment. However, if large quantities of secondary resources are used pre-maturely (as opposed to taking measures now to collect and stockpile for future recovery), the opportunity to economically capture critical elements as by-products of current primary production is compromised or lost.
We Need a Holistic Paradigm	Material supply issues must be looked at holistically due to the broad range of end-use applications and competing demands for minerals/metals/elements. In other words, policy decisions cannot be looked at in isolation. Although the scope of this study is focused on the availability of material sets required for emerging technologies, the implications of material selection on water use and emissions, as well as land and water demands associated with operating each technology choice must not be overlooked. A holistic, full life-cycle approach is needed.

[3] Source: "Minerals, Critical Minerals and the U.S. Economy", National Research Council (2008)

The dynamics between primary (virgin ore) and secondary (old scrap) supply is complicated and availability of each at any given point in time is a function of the respective answers to the questions summarized in Table 2 and Table 3. The answers to each of the questions raised will **change** over time. Policy makers, voters and all stakeholders in the supply chain need to understand how they might influence the answers to each of these questions and must be cognizant of the relative certainty we have in the data available at any given point in time. Furthermore, society needs to continually foster the proper expertise to interpret the data collected and to develop innovative solutions to unlock new potential resources. It must invest in research within *all related disciplines* (engineering, physical and social sciences) so future generations have the capacity and expertise to continually answer these questions. The United States needs to be cognizant of how other countries are currently addressing these questions and to what extent international cooperation will be required to ensure a reliable and sustainable raw material supply.

Table 2: The Five Dimensions of Mineral Availability

Geologic Availability	*Does the mineral resource exist?*
Technical Availability	*Can we extract and process it?*
Environmental & Social Availability	*Can we produce it in an environmentally and socially responsible manner?*
Political Availability	*How do governments influence primary availability through their policies and actions?*
Economic Availability	*Can we produce it at a cost users are willing and able to pay?*

Adapted from "Minerals, Critical Minerals and the U.S. Economy", National Research Council (2008)

Table 3: The Four Dimensions of Recyclability

Technical Availability	*Is technology available to sort, separate and recover material, and is an efficient post-consumer collection network in place?*
Environmental & Social Availability	*Can we develop socially and environmentally acceptable waste diversion programs, and can we encourage more consumer participation?*
Political Availability	*How do governments influence secondary availability through their policy and actions?*
Economic Availability	*Are adequate economies of scale in place to produce secondary materials at a cost users are willing and able to pay?*

Adapted from "Minerals, Critical Minerals and the U.S. Economy", National Research Council (2008)

Presentation, Randy Kirchain,
Considering Resource Availability for Energy Technologies

Considering Resource Availability for Energy Technologies

Randolph Kirchain, Frank Field, and Rich Roth

Materials Systems Laboratory
Department of Materials Science & Engineering and
Engineering Systems Division

Thanks to Many MSL Collaborators:
Elisa Alonso, Jeremy Gregory, and Elsa Olivetti

MSL Views on Scarcity

- **Generally, agree with economic theory**
  - **Market solves most issues with scarcity**
- **So … Don't worry, be happy?**
- **Unfortunately, we aren't so lucky**
- **Scarcity occurs when: Total cost to extract exceeds market value**
  - **Can cause problems for novel technologies**
- **Intervention may improve social welfare**
  - **Must be very careful**

Key Points

1. **Short term events matter**
2. **Energy costs may exacerbate economic availability** (ironically)
3. **Recycling Reduces Some Impacts of Scarcity**
4. **Recycling Faces Challenges** (particularly for "high-tech" materials)
5. **Intervention may be valuable** (must be selected carefully)
6. **Significant information / analytical gaps**

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Energy and Recycling for Scarcity: Slide 3

1. Short Term Events Matter

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Energy and Recycling : Slide 4

Short Term Events Matter

Materials technology use is undeniably path-dependent

- **Incumbency matters**
  Materials transitions face activation barriers
  - **Invested capital**
  - **Knowledge**
  - **Trust**
- **Transient events matter**
  Sufficient perturbations can shift usage to other paths
  - **Even when price spikes are temporary the effects on firms and societies technology trajectory can be permanent**

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Energy and Recycling for Scarcity: Slide 5

Short Term Events Matter

A Historic Example of Short Term Materials Constraint

- **Cobalt in the Late 1970's**
- **Zaire compared to World in 1977**
  - **Population** 0.04%
  - **GDP** 0.09%
  - **Cobalt resources** 40%
- **Small scale rebellion in 1977 led to:**
  - **Short term constraint**
  - **Global speculation**

Sources: Adelman, K. L. *R. Afr. Soc.* **1978, v77.** Blechman and Sloss. *National Security and Strategic Minerals*, 1985. Canadian Minerals Yearbook 1886-2004. and USGS Mineral Yearbook and Mineral Commodity Summary 1932-2006,

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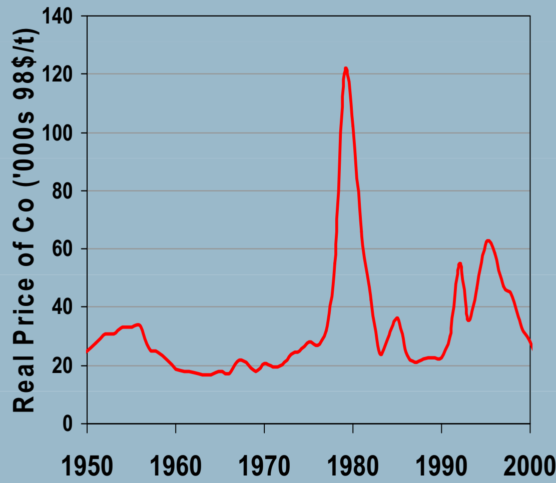
Energy and Recycling for Scarcity: Slide 6

Why Worry about Resource Use Now?

Some Impacts on Materials Producers are Permanent

Primary Outcome: Price Increase



Alonso, E., et al. (2007). "Material Availability and the Supply Chain: Risks, Effects, and Responses." ES&T. 41(19): 6649-6656.

- **Supply constraint led to price increase that led to changes in ..**
  - **Geography**
    - Supply relocation
  - **Operations**
    - Recycling
    - Stockpiling
  - **Technology**
    - Process efficiency
    - Materials substitution
- **Some industries that switched away from Cobalt, have never switched back.**

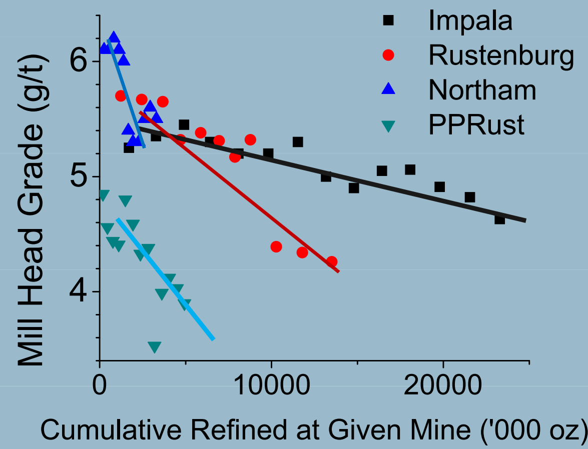
Even though price changes were temporary, *effects to firms were permanent*

2. Energy costs may exacerbate economic availability (ironically)

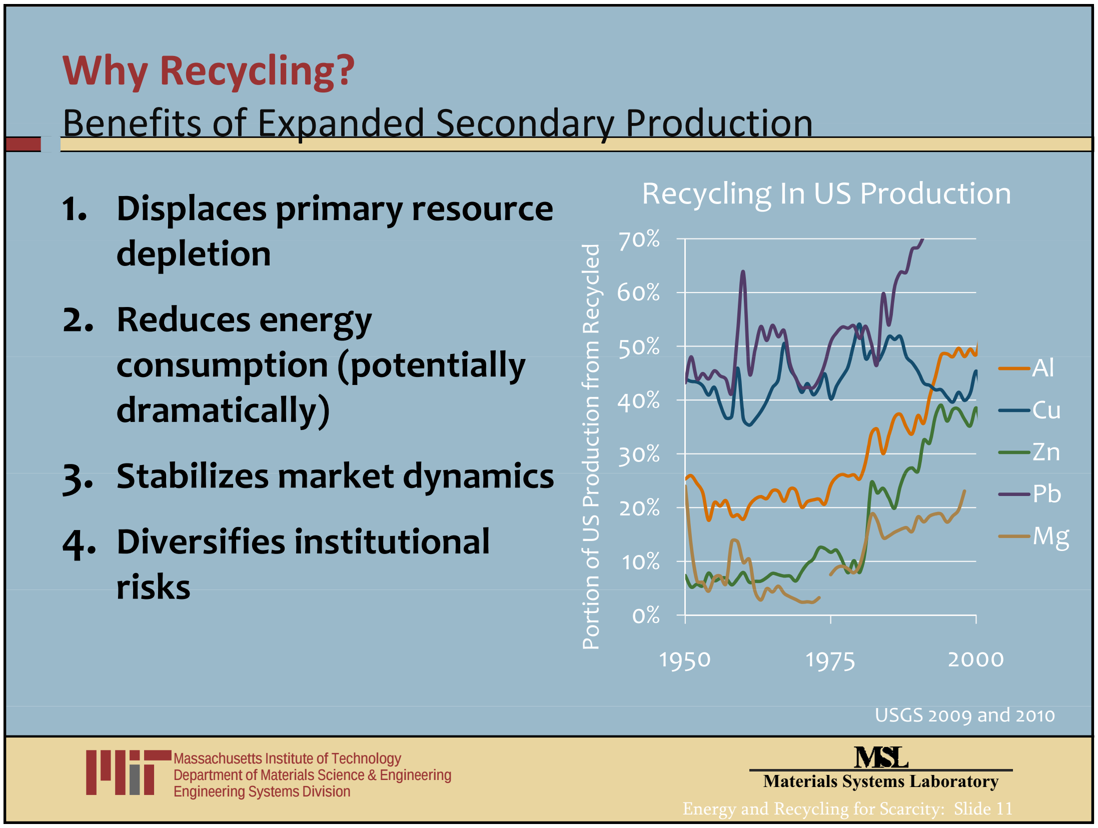
Energy as an Economic Driver of Scarcity

Important to not forget given future changes in market

- **Energy is a major cost of extraction**
- **Generally related to ore grade, but technology has outpaced ore grade degradation**
- **Going forward will this continue?**
- **Don't forget (unlike helium) most non-fuel resources are not lost, only altered in concentration & mineralogy**



3. Recycling Reduces Some Impacts of Scarcity


Why Recycling?
Benefits of Expanded Secondary Production
1. Displaces primary resource depletion
2. Reduces energy consumption (potentially dramatically)
3. Stabilizes market dynamics
4. Diversifies institutional risks
Recycling In US Production
Portion of US Production from Recycled
70%
60%
50%
40%
30%
20%
10%
0%
1950
1975
2000
Al
Cu
Zn
Pb
Mg
USGS 2009 and 2010
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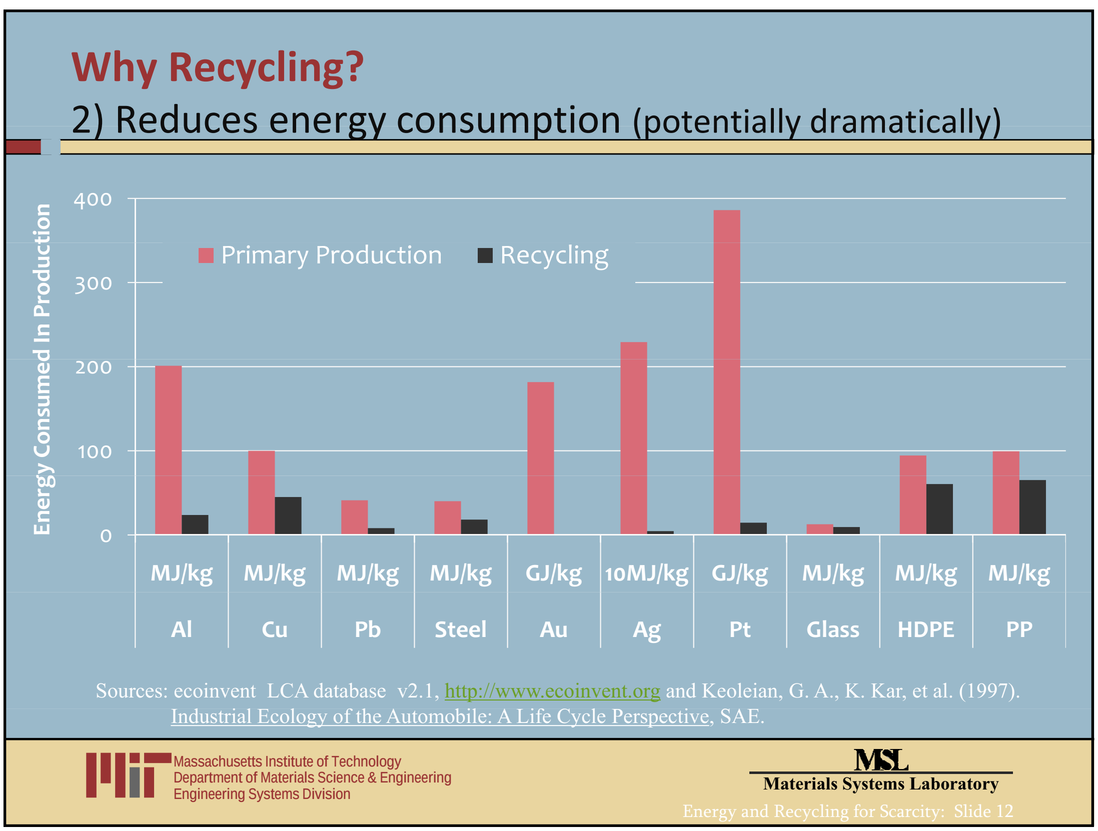
Why Recycling?
2) Reduces energy consumption (potentially dramatically)
Energy Consumed In Production
400
300
200
100
0
Primary Production
Recycling
MJ/kg Al
MJ/kg Cu
MJ/kg Pb
MJ/kg Steel
GJ/kg Au
10MJ/kg Ag
GJ/kg Pt
MJ/kg Glass
MJ/kg HDPE
MJ/kg PP
Sources: ecoinvent LCA database v2.1, http://www.ecoinvent.org and Keoleian, G. A., K. Kar, et al. (1997). Industrial Ecology of the Automobile: A Life Cycle Perspective, SAE.
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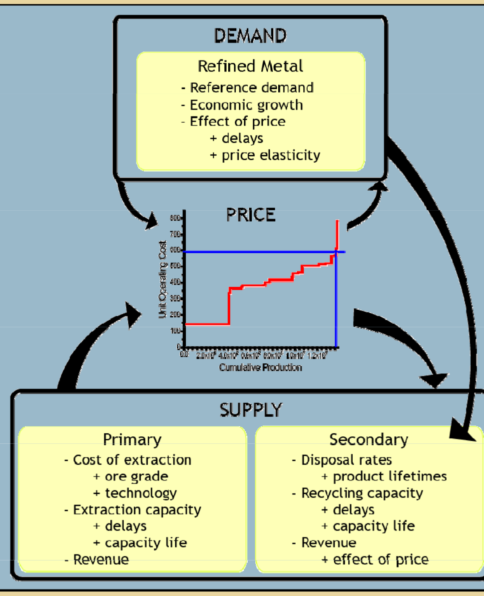
Energy and Recycling for Scarcity: Slide 12

Why Recycling?

3) Stabilizes Market Dynamics

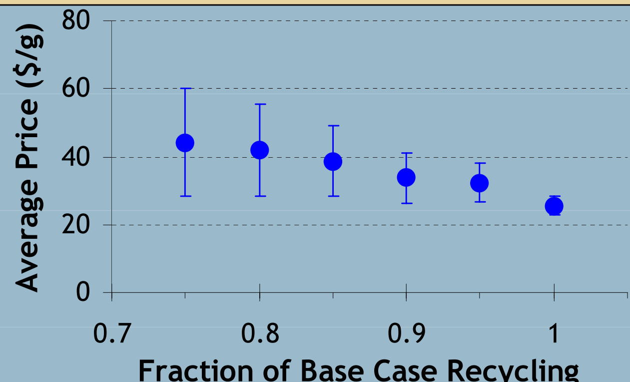
- **Manufacturer concerns about materials**
  - **Average and variance of cost**[1]
  - **Sufficiency to meet demand**[2]
- **How does recycling effect these?**
  - **Empirical not possible**
  - **Simulation of**
    - Product Demand
    - Primary and Secondary Supply
    - Market clearing



1. Hayenga 1979, Campbell 1989, Urbance 2002, Nelles 2009.
2. Fisher 1997, Lensing 2003, Kleindorfer 2005, Sheffi 2005.

Model-based Conclusion:

Novel Value of Recycling as a fast-responding supply



Alonso et al. 2009 & 2010

High Levels of Recycling…

- **Reduces use of primary supply - slows down ore degradation**
- **Stabilizes inventory of metal and hence price**
  - Experiences less significant price variability, Recovers more quickly
- **Reduces supply chain risk**

Why Recycling?

4) Diversifies institutional risks

- **Secondary production often occurs in different locations and firms than primary production**
- **May not be susceptible to co-product limitations**
- **Generally, secondary production requires less capital investment**

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4. Recycling Faces Challenges

(particularly for “high-tech” materials)

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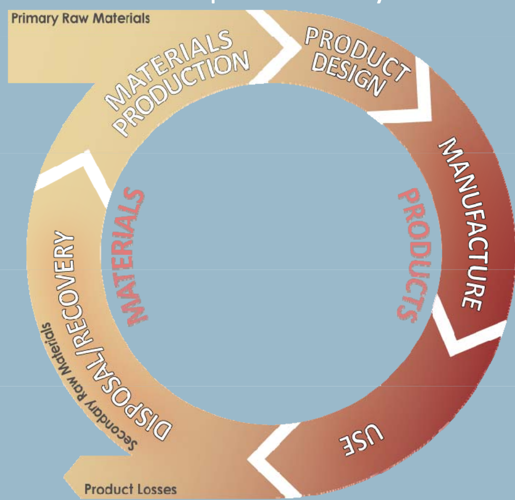
Realizing Recycling
Challenges for Expanded Secondary Production

The Material | Product Cycle



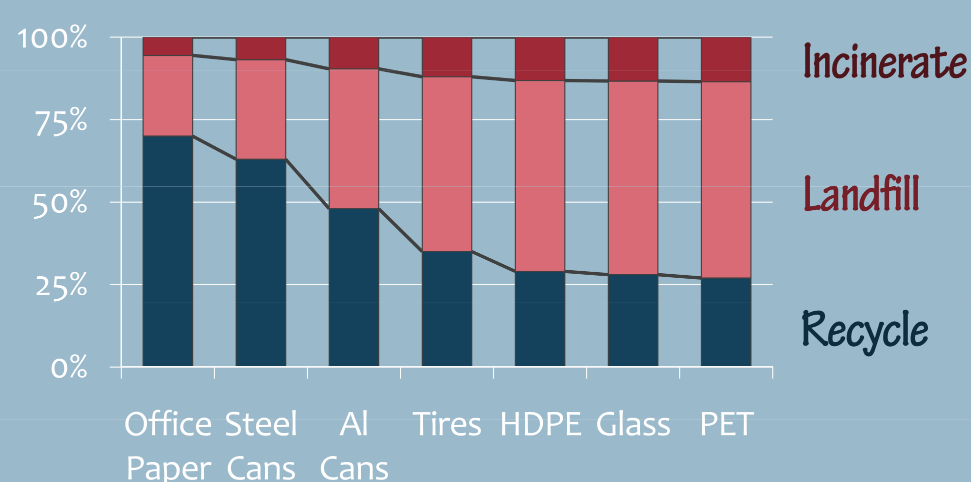
Recycling is an emergent property

a. Technological barriers
   - Co-mingling / Segregation
   - Quality variability (Peterson 1999, Gaustad 2009)

b. Socio-economic barriers
   - Low consumer participation (Watts, Jones et al. 1999; Morgan and Hughes 2006; Das and Hughes 2006)
   - Market resistance (Vigeland 2001, Woodward 1997; Gesing 2004)
   - Transactions costs (Ehrenfeld & Gertler 1997)
   - Source-sink dislocation (Gregory & Kirchain 2009)

c. Policy
   - Positives & negatives

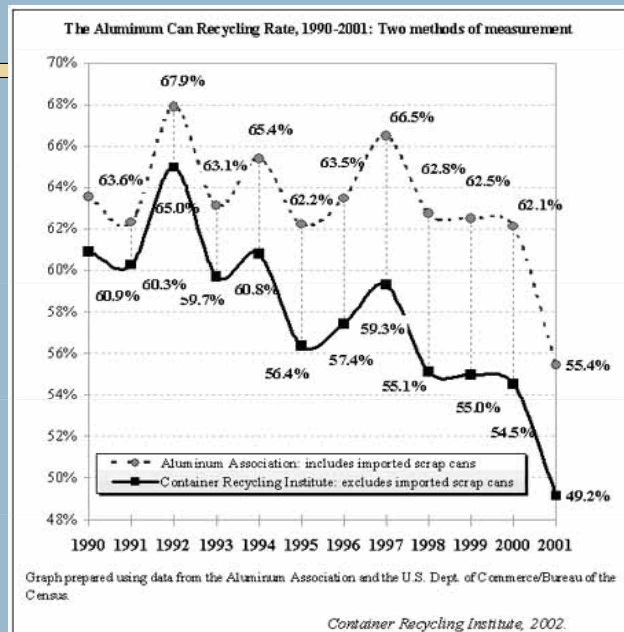
Realizing Recycling:
Low Consumer Participation Hampers Recycling



Municipal Solid Waste in the United States: 2007 Facts and Figures. Office of Solid Waste, US EPA

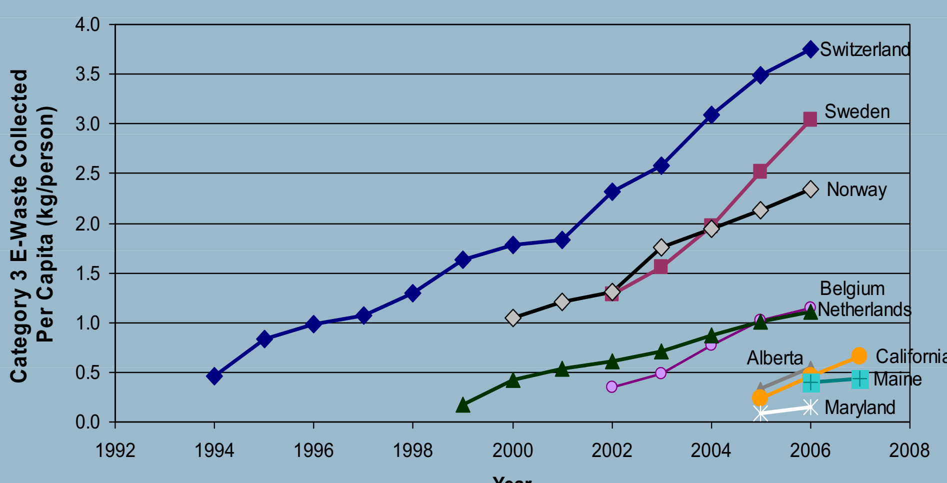
Realizing Recycling:

Low Consumer Participation Hampers Recycling



Recycling Policy has Potential Positives & Negatives

Positive: Extended producer responsibility policies drive up recovery

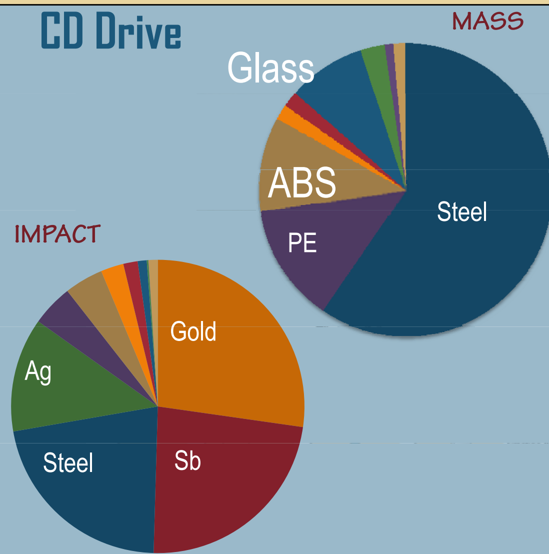


Fredholm 2008

Recycling Policy has Potential Positives & Negatives

Negative:
Extended producer responsibility policies can incentivize recovery of bulk materials to detriment of scarce materials

Huisman 2004; Hagelüken 2006, 2008



Mohite & Zhang, Texas Tech, IEEE 2005.

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5. Intervention may be valuable (must be selected carefully):
Many disparate analyses of issues, Missing big picture

Options
- **Stockpiling**
  - Theory suggests value of buffer
  - Historic examples of stockpiles exacerbating price instability
- **Supply-side Subsidy**
  - Investment or Investment guarantee, Price supports,
- **Demand-side Influence**
  - Purchasing policy
- **Technology development support**
  - Efficiency, Recycling, substitution, …
- **Legalized Collusion**
  - Roadmapping

Probably Best First Step
- **Information and transparency**
- **Comprehensive analysis of interaction of these policies**
  - **Stockpiling**
    - How big is big enough?
    - Effective control rules
  - **Tech development**
    - Which strategies (not technologies) are most effective?
  - **Collusion**
    - At what level of technology?

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6. Many Information & Analytical Gaps

- **Information**
  - **Supply characteristics**
    - Responsiveness
  - **Demand characteristics**
    - Evolutionary
      - Elasticity
    - Revolutionary
      - Cost structure
  - **Substitution characteristics**
- **Analytical**
  - **Metrics**
  - **Models**
    - Supply-demand simulation of interacting markets
    - Understanding of effects of interventions (stockpile mgt policies…)
- **Transfer**
  - **Roadmapping activities have demonstrated effective in many contexts**

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Key Points

1. Short term events matter
2. Energy costs may exacerbate availability
3. Recycling Reduces Some Scarcity Impacts
4. Recycling Faces Challenges
   (particularly for "high-tech" materials)
5. Intervention may be valuable
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Presentation, Leonard Surges,
Advantage Canada: Materials-Related Policies


Advantage Canada
Materials-Related Policies

APS – MITEI – MRS Workshop: Critical Elements for New Energy Technologies
Cambridge, MA

Leonard Surges
Natural Resources Canada

Natural Resources Canada / Ressources naturelles Canada

April 29, 2010

Canada

Introduction

- Canada works with the United States through the Clean Energy Dialogue and many other mechanisms
  - R&D is a focus to advance clean energy technologies.
- Canada offers access to energy, materials and markets
  - Provinces are taking steps to stimulate clean energy investments.
- *Advantage Canada: Building a Strong Economy for Canadians* aims to build key competitive economic advantages
  - Tax, Fiscal, Entrepreneurial, Knowledge and Infrastructure.
- Canada is a leading mineral and metal producer and exporter
  - Canada has an open economy and imports many materials and products;
  - Value chains are global and it is difficult to assess risks at the national level.
- A value-added mining cluster is supported by a large and diverse landmass and by policies that are **not** material specific.
- The Canadian exploration and mining sectors have a global focus.
- Companies process, market and recycle rare metals in Canada and abroad.

Domestic Investment Climate

- The Crown owns subsurface resources and manages public lands
  - Governments establish framework policies;
  - Private investment creates economic opportunities and generates revenues.
- Public geoscience generates knowledge used to identify exploration targets
  - Targeted measures include the Targeted Geoscience Initiative (TGI) and Geoscience for Energy and Minerals (GEM) Program;
  - Canada is a leader in geomatics;
  - Data and assessment reports are accessible;
  - Claims can be staked online but are subject to work requirements.
- Claims and leases can be transferred.
- Highly qualified personnel and suppliers enhance performance.
- Aboriginal participation can create mutual benefits.
- Tax measures reflect business and competitive realities
  - Companies without operating cash flow rely on access to equity financing;
  - Eligible Canadian Exploration Expense (CEE) can be "flowed through" to investors;
  - Tax credits may provide added incentives;
  - Sales tax reform, elimination of capital taxes, reduced corporate income tax rates and other measures reduce capital cost, accelerate payback, enhance cash flow and reduce risks.
- Public expectations remain balanced.
- Governments are committed to improve regulatory performance, ensure environmental protection and enhance competitiveness.
- Foreign investors receive national treatment.
- Governments may fund key regional infrastructure, directly or indirectly.

Canada's Natural Resources – *Now and for the Future* 3

Concluding Remarks

- Canada works with the United States and other partners to
  - Develop clean energy technologies and materials for clean energy production and use;
  - Challenge export restrictions and other trade barriers.
- Policies that are generally **not** material-specific support Canada's position as a global leader in sustainable mineral resource development
  - Tax rates and barriers to foreign investment and trade are low;
  - Canada's influence extends to most countries and regions with mineral potential.
- Integrated producers supply certain rare metal coproducts
  - Output of main product and quality of operating assets drive supply.
- Smaller companies are advancing projects that could eventually increase rare metal reserves and production, in Canada and abroad
  - Lithium, rare earths (REE) and other rare metals are attracting growing interest;
  - In 2008, 11 operators spent $16 million at 18 REE projects in Canada;
  - New mines may not ensure availability of value-added materials/components.
- Some Canadian companies are experienced rare metal processors, distributors and recyclers with global market intelligence and reach.
  - Mitsubishi Corporation partnered with Neo Material Technologies Inc. to commercialize REE opportunities outside China.

Canada's Natural Resources – *Now and for the Future* 4

Diana Bauer, Response to Mr. Sibley's Presentation
Marc Humphries, Response to Mr. Sibley's Presentation
Brad Roscoe, Response to Dr. Lancaster's Presentation

Diana Bauer – DOE – Office of Policy and International Affairs

Formal response to Scott Sibley

Just as tellurium is co-produced with copper, materials policy is co-produced with energy policy. The question, then, is given that materials policy is not the primary focus, where should energy policymakers and R&D investors direct their attention in material systems? The mineral commodity information developed by Sibley and colleagues at USGS is invaluable for understanding material flows, including the relative importance of energy sector demands and supply vulnerabilities deriving from production or reserve concentration. This is a strong foundation for any thinking about material implications of proposed energy policies.

Understanding the dynamics of mineral supply economics is important. With a ramp up in investment and deployment of clean energy technology in the US and globally, material use patterns for energy technologies will shift. This may affect long term price trends and more likely short term price volatility, both of which could affect the rate of clean energy technology diffusion. Economic energy policy ideally works with the market to prevent or dampen short term perturbations while allowing long term fundamentals to play out.

Longer term energy policy has technology research and development as its basis. There is certainly the opportunity to both collaborate and compete globally in this research. Ultimately, having an array of technical options using various materials gives future flexibility through substitution. Thus it is wise to support clean energy technology research that uses a diverse set of materials, such as across the PV material space identified by Wadia et. al. (2009). As described by Bae, research should also address recycling, efficient material use, and environmentally sound mining, separation, and purification processes.

MITEI and APS Workshop on:

Critical Elements for New Energy Technologies
April 29, 2010

Prepared response by Marc Humphries, Energy and Mineral Policy Analyst of the Congressional Research Service to the White Paper delivered by Scott F. Shelby of the USGS.[1]

Tracking Critical Elements in the United States: Supply of and Demand for Selected Energy Related Mineral Commodities

The paper presented by Scott Shelby provides a useful framework from which to examine primary and secondary supply of raw material and the physical and economic factors that could restrict supply. The section on the concentration of production and reserves raises the important issue of supply vulnerability. Is the U.S. vulnerable to supply disruptions of critical elements for new energy technologies?

The tracking of critical elements (those essential to U.S. national security and economic well-being) for new energy technologies reveals a complex global supply chain and numerous end-use applications. Placing the supply chain in the global context is likely to be unavoidable in the short and long term even when implementing U.S. mineral policy.[2] U.S. mineral policy places emphasis on developing domestic supplies of critical materials and the domestic private sector to produce and process those materials. But some raw materials do not exist in economic quantities in the United States, while processing, manufacturing and other downstream ventures in the U.S. may not be competitive with facilities in other regions of the world. However, there may be some public policies enacted or executive branch measures taken to offset the U.S. disadvantage of its potentially higher cost operations. The current goal of U.S. mineral policy is to promote an adequate, stable and reliable supply of materials for U.S. national security, economic well-being and industrial production.

The global supply chain of critical elements is being examined by industry and government to determine where and how to develop reliable sources of critical (and other) materials and downstream processes needed for new energy technologies and defense applications. If a mine-to-market integration emerges in the United States, how

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[1] The views presented in this response are those solely of the author and not necessarily those of the Congressional Research Service or Library of Congress.

[2] U.S. mineral policies provide a framework for the development of domestic metal mineral resources and for securing supplies from foreign sources. Specifically, the Mining and Minerals Policy Act of 1970 (30 U.S.C. §21a.) declared that it is in the national interest of the United States to foster the development of the domestic mining industry "... including the use of recycling and scrap." The National Materials and Minerals Policy, Research and Development Act of 1980 (30 U.S.C. 1601), among other things, declares that it is the continuing policy of the United States to promote an adequate and stable supply of materials necessary to maintain national security, economic well-being and industrial production, with appropriate attention to a long-term balance between resource production, energy use, a healthy environment, natural resources conservation, and social needs.

much of U.S. demand would it satisfy? An important component of this examination could be an analysis of the structure of the industry. This analysis could illuminate where the industry is investing and how firms are securing project financing. Further, industry studies could show how firms are collaborating (or not) or the potential for collaboration (e.g., joint ventures and consortium) to develop those essential elements for new energy technologies.

Policy Questions

What are the policy questions, the legislative hook? Is the critical element policy question about reducing import dependence? Is it to assure access to reliable supplies regardless of location or producer? Will there be autarkic calls for mineral independence as there are for energy independence? Where does Congress want to invest federal resources and what returns on investment should Congress and the American public expect? How are environmental protection and regulation going to be addressed? What tools could be used to place certain public lands off-limits and for Congress to better grasp the full life-cycle effects of mining, including water issues. Through the legislative and appropriation processes, Congress can continue to address these questions.

Questions We Grapple With

- What are the critical elements essential for the new energy technologies and to what degree does the U.S. depend on foreign sources for these elements?
- What foreign government mineral development policies and regulations help or hinder multiple source development of critical materials?
- What policies help or hinder development of domestic production of critical elements?
- What downstream processes are critical? For example, is the manufacture of neodymium-rich magnets critical to the U.S.?
- To what extent should Congress increase funding for critical materials research and development (R&D), secondary supply recovery technology and infrastructure, and loan guarantees that could lead to increased access to stable and reliable supplies?
- To what extent should the U.S. partner with countries affiliated with the Organization for Economic Cooperation and Development (OECD) or other international partnerships to seek stable supplies?
- To what extent should/could Congress consider enhancing U.S. mineral information and analysis so it could be elevated to the level of the Energy Information Administration (EIA)?

Need for Information

1. Domestic and global geologic assessment of critical elements. An assessment that includes critical elements located on public lands.
2. Life-cycle analysis of each critical element for new energy technologies.
3. Frequent and timely industry analyses including investment analysis focusing on the critical element supply chain and end-use applications.
4. More frequent analyses of new/emerging technologies associated with critical element processing and end-use applications.

Comments on Helium Supply Issues

Brad Roscoe - Schlumberger

One very important application of helium to the energy sector was not mentioned in the information provided. Specifically, an isotope of helium, He-3, is used in detectors in neutron porosity tools, one of the key instruments used to locate hydrocarbons, estimate petroleum reserves, and make production decisions. The neutron device is particularly used to establish the rock and fluid parameters which help determine these properties. Thus, uncertainties in these parameters can have a large impact. For example, a seemingly small uncertainty in the reservoir porosity (the fraction of the geological formation that is porous) can result in uncertainties in reserves in the tens to hundreds of millions of barrels oil-equivalent, depending on the size and quality of the reservoir.

Historically, He-3 has been supplied as a by-product of the nuclear weapons stockpile. Recently, He-3 has been in short supply due to the roll-out of new portal monitoring systems for detecting contraband materials. This supply problem has resulted in significant actions by the US government to address this problem and is very evident by the April 22, 2010 hearing by the House Subcommittee on Investigations & Oversight , entitled "Caught by Surprise: Causes and Consequences of the Helium-3 Supply Crisis".

At the April 6, 2010 "Workshop on Helium-3" sponsored by the American Association for the Advancement of Science, possible alternative supplies of He-3 were discussed. On possible supply that is being actively discussed, is the extraction of He-3 from the National Helium Reserve. It is projected that 2000 to 4000 liters/year of He-3 could be extracted from this reserve compared to the current supply path which can produce about 8000 liters/year. Hence, this resource would have significant impact.

It is my view that one should not discuss the national helium reserve issues without at least mentioning this application to another pressing issue.

Jon Price,
Leading Producers of Energy-Critical Elements

Table 1. Global production and leading producers of selected elements (with percentage of world production in 2009)[1].

Element	Global production (tonnes)	Leading Producer	2nd Producer	3rd Producer
Aluminum[2]	201,000,000	Australia (31%)	**China (18%)**	Brazil (14%)
Arsenic[3]	53,500	**China (47%)**	Chile (21%)	Morocco (13%)
Cadmium[4]	18,800	**China (23%)**	Korea (12%)	Kazakhstan (11%)
Cobalt	62,000	Congo (40%)	Austalia (10%)	**China (10%)**
Copper	15,800,000	Chile (34%)	Peru (8%)	USA (8%)
Gallium[5]	78	**China**	Germany	Kazakhstan
Germanium[6]	140	**China (71%)**	Russia (4%)	USA (3%)
Gold	2,350	**China (13%)**	Australia (9%)	USA (9%)
Helium[7]	22,900	USA (63%)	Algeria (19%)	Qatar (12%)
Indium[8]	600	**China (50%)**	Korea (14%)	Japan (10%)
Iron[9]	2,300,000,000	**China (39%)**	Brazil (17%)	Australia (16%)
Lead	3,900,000	**China (43%)**	Australia (13%)	USA (10%)
Lithium[10]	18,000	Chile (41%)	Australia (24%)	**China (13%)**
Platinum	178	South Africa (79%)	Russia (11%)	Zimbabwe (3%)
Rare earths[11]	124,000	**China (97%)**	India (2%)	Brazil (1%)
Selenium[12]	1,500	Japan (50%)	Belgium (13%)	Canada (10%)
Tellurium[13]	>200	Chile	USA	Peru
Zinc	11,100,000	**China (25%)**	Peru (13%)	Australia (12%)

[1] Data mostly from U.S. Geological Survey (2010); uranium data from World Nuclear Association (24 December 2009, World Nuclear Association, 2009, http://www.world-nuclear.org/info/uprod.html.) Production figures are in tonnes (metric tons).
[2] Bauxite and alumina production, not aluminum metal. Contained Al is approximately 69,500,000 tonnes.
[3] Production figures in tonnes of arsenic trioxide; produced from arsenopyrite and as a byproduct of Cu, Au, and Pb. Contained As is approximately 40,500 tonnes.
[4] Production (as a byproduct of Zn) figures are for refinery production, not where the metal was mined.
[5] Byproduct primarily of Al, some as a byproduct of Zn.
[6] Byproduct of some Zn and Pb-Zn-Cu ores; resources also in coal; leading producers assumed to be same as for Zn.
[7] Byproduct of some natural gas deposits; production from China not available.
[8] Byproduct primarily of Zn and Cu; resources in Sn and W deposits; figures are for refinery production, not where the metal was mined.
[9] Mine production of iron ore. Contained Fe is approximately 1,600,000,000 tons.
[10] U.S. production withheld and not included in the global total; the USA may be the third largest producer, based on the latest published figures (Driesner and Coyner, 2007).
[11] Rare earth elements (lanthanides) include La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu; production figures are in tonnes of rare earth oxide.
[12] Byproduct of Cu production; figures are for refinery production, not where the element was mined.
[13] Byproduct of Cu production; leading producers assumed to be same as for Cu.

Not included (but could be) in this table

Chromium	23,000,000	South Africa (42%)	India (17%)	Kazakhstan (16%)
Manganese	9,600,000	**China (25%)**	Australia (17%)	South Africa (14%)
Molybdenum	200,000	**China (39%)**	USA (25%)	Chile (16%)
Nickel	1,430,000	Russia (19%)	Indonesia (13%)	Canada (13%)
Niobium	62,000	Brazil (92%)	Canada (7%)	
Palladium	195	Russia (41%)	South Africa (41%)	USA (6%)
Silver	21,400	Peru (18%)	**China (14%)**	Mexico (12%)
Thallium[14]	10			
Tin	307,000	**China (37%)**	Indonesia (33%)	Peru (12%)
Uranium	43,800	Canada (21%)	Kazakhstan (19%)	Australia (19%)
Vanadium	54,000	**China (37%)**	South Africa (35%)	Russia (26%)

[14]Byproduct of Zn, Cu, and Pb production.

APS – MITEI – MRS Workshop
"*Critical Elements for New Energy Technologies*"

April 29, 2010

8:00 AM – 6:30 PM
Location: Cambridge, MA
Continental breakfast and lunch will be provided on premises.

8:00 – 8:30	AM	Continental Breakfast	
8:30 – 8:45	AM	**Welcome & Overview** Ernest J. Moniz Professor of Physics Cecil & Ida Green Distinguished Professor Director, MIT Energy Initiative Robert L. Jaffe, MIT APS POPA Study Co-chair	
8:45 – 9:45	AM	**Rare Earths & Related Issues** Keynote Speaker, Anthony Mariano *"The Nature of Economic REE and Y Minerals on a World Level"*	Moderator: K. Gschneidner
9:45 – 10:45	AM	**Cadmium/Tellurium & Related Issues** Keynote Speaker, David Eaglesham First Solar, Inc. *"Tellurium for Photovoltaics"*	Moderator: I. Turnbull
10:45	AM	Coffee Break	
11:00 – 12:00	PM	**Helium & Related Issues** Keynote Speaker, James Lancaster National Academies of Science *"Selling the Nation's Helium Reserve"*	Moderator: A. Hurd
12:00 – 12:45	PM	**General Discussion – First 3 Topics/Issues**	Moderator: F. Houle
12:45	PM	Lunch	

1:30 – 2:30	PM	**Substitutional Research in Physics, Chemistry & Material Science** Keynote Speaker, Cyrus Wadia Lawrence Berkeley National Laboratory *"Mined Resource Constraints on Solar Energy and Battery Storage Potential & The Rare Earth Element Debate as Seen From the White House."*	Moderator: D. Milliron
2:30 – 3:30	PM	**Tracking Critical Elements in the U.S.** Keynote Speaker, Scott Sibley U.S. Geological Survey *"Supply of and Demand for Selected Energy Related Mineral Commodities"*	Moderator: M. Hitzman
3:30	PM	Coffee Break	
4:00 – 5:00	PM	**Materials Policies of Other Nations** Keynote Speaker, Dr. Jung-Chan Bae Korea Institute of Industrial Technology (KITECH) *"Strategies and Perspectives for Securing Rare Metals in Korea"*	Moderator: A. King
5:00 – 5:45	PM	**General Discussion – Second 3 Topics/Issues**	Moderator: R. Eggert
5:45 – 6:15	PM	**Open Discussion**	Moderators: R. L. Jaffe J. Price
6:15 – 6:30	PM	**Summary & Concluding Remarks** Jonathan Price, Nevada Bureau of Mines & Geology University of Nevada, Reno APS POPA Study Co-chair	

Please plan to join us for a relaxing dinner at
Bambara Restaurant
25 Land Boulevard
Cambridge, MA 02141
(617) 868-4444
7:30 PM

APS – MITEI – MRS Workshop
"*Critical Elements for New Energy Technologies*"

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ACRONYMS

APS	American Physical Society
ARPA-E	Advanced Research Projects Agency-Energy
Bcf	Billion Cubic Feet
BLM	Bureau of Land Management
CA	California
CAGR	Compound Average (Annual) Growth Rate
CdTe	Cadmium-Tellurium
CEQ	Council on Environmental Quality
CIGS	$CuInGaSe_2$
CPV	Concentrating Photovoltaic
CRS	Congressional Research Service
DHS	Department of Homeland Security
DOD	Department of Defense
DOE	Department of Energy
ECE	Energy-Critical Element
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Agency
EPA	Environment Protection Agency
GDP	Gross Domestic Product
GW	Giga Watts = 10^9W
HEV	Hybrid Electric Vehicle
HREE	Heavy Rare Earth Element
IPCC	Internationl Panel on Climate Change
IT	Information Technology
KCMIC	Korea-China Material Industry Committee
kg	Kilogram
KITECH	Korea Institute of Industrial Technology
KORES	Korea Resource Corporation
KRMC	Korea Rare Metals Center
kWh	Kilowatt-Hour
LBNL	Lawrence Berkeley National Labs
LNG	Liquefied Natural Gas
LREE	Light Rare Earth Element
Mcf	Thousand Cubic Feet
MITEI	Massachusetts Institute of Technology's Energy Initiative
MKE	South Korea Ministry of Knowledge & Economy
MMcf	Million Cubic Feet
MRI	Magnetic Resonance Imaging
MRS	Materials Research Society
MSL	Materials Systems Laboratory
Mt	Million Tons
MW	Million Watts
NiMH	Nickel Metal Hydride
NRC	National Research Council
NSTP	National Science and Technology Program
OECC	Office of Energy and Climate Change
OSTP	Office of Science and Technology Policy
PDAC	Prospectors and Developers Association of Canada
PGE	Platinum Group Element
PGM	Platinum Group Metal
POPA	Panel on Public Affairs (APS)
PV	Photovoltaic
R&D	Research & Development
R/P	Reserves to Production Ratio
REE	Rare Earth Element
REO	Rare Earth Oxide
SCE	Strategic Critical Element
TFPV	Thin-Film Photovoltaic
TW	Terra Watts = 10^{12}W
UN	United Nations
USBM	US Bureau of Mines
USGS	US Geological Survey
W	Watts
x-Si	Crystalline Silicon

Elements

Ag	Silver
Al	Aluminum
Au	Gold
Bi	Bismuth
C	Carbon
Ca	Calcium
Cd	Cadmium
Ce	Cerium
Cl	Chlorine
Co	Cobalt
Cu	Copper
Dy	Dysprosium
Er	Erbium
Eu	Europium
F	Flourine
Fe	Iron
Ga	Gallium
Gd	Gadolinium
Ge	Germanium
He/He-4	Helium-4
He-3	Helium-3
Ho	Holmium
In	Indium
Ir	Iridium
La	Lanthanum
Li	Lithium
Lu	Lutetium
Mg	Magnesium
Mn	Manganese
Mo	Molybdenum
Na	Sodium
Nb	Niobium
Nd	Neodymium
Ni	Nickel
O	Oxygen
Os	Osmium
P	Phosphorus
Pb	Lead
Pd	Palladium
Pm	Promethium
Pr	Praseodymium
Pt	Platinum
Rh	Rhodium
Ru	Ruthenium
S	Sulfur
Sb	Antimony
Sc	Scandium
Se	Selenium
Si	Silicon
Sm	Samarium
Sn	Tin
Ta	Tantalum
Tb	Terbium
Te	Tellurium
Th	Thorium
Ti	Titanium
Tm	Thulium
U	Uranium
W	Tungsten
Y	Yttrium
Yb	Ytterbium
Zn	Zinc
Zr	Zirconium

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