Preface

Recent stresses in the global market of rare earth elements have brought the sustainable supply of *critical materials* to the forefront in the United States and other industrialized countries. In addition to rare earth elements (e.g. neodymium, terbium, dysprosium and ytterbium) and platinum group metals (e.g. platinum, palladium, rhodium, ruthenium, iridium, and osmium), significant amounts of copper, silver, gold, manganese, lithium, titanium and gallium will be needed to build the sustainable products, processes, and industries of the 21st century. During the last 2 years, the supply/utilization of *critical materials* in renewable energy technologies has been discussed in numerous symposia, reports and publications. However, no focused symposium and in-depth report have been devoted to the role of separations science and engineering (SSE) in the areas of sustainable extraction, recovery, and recycling, as well as potential replacements of critical metals with earth-abundant elements. Thus, we proposed to organize a 1-day symposium devoted to *"Ensuring the Sustainability of Critical Materials and Alternatives: Addressing the Fundamental Challenges in Separation Science and Engineering"*, jointly sponsored by the American Institute of Chemical Engineers (AIChE) and the American Chemistry Society (ACS). The overall objectives of the symposium were to:

- Discuss the key and enabling role of SSE in ensuring a sustainable supply and utilization of critical materials
- Bring into focus cross-cutting research and educational needs and Scientific Grand Challenges in SSE associated with the sustainable extraction, recovery, recycling and purification of critical materials.
- Communicate these research needs to the SSE and broader science/engineering community.

This report summarizes the main findings of the symposium.

Ensuring the Sustainability of Critical Materials and Alternatives:

Addressing the Fundamental Challenges in Separation Science and Engineering

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Executive Summary

During the symposium, the discussion was organized around two major themes: 1) R&D and technology needs and 2) education and training of the future workforce in the field of separations sciences and engineering (SSE) as it applies to critical materials. Key findings from the symposium include:

- SSE is a broad discipline that integrates basic scientific and engineering knowledge from many fields including: (i) analytical, physical, inorganic, polymer and supramolecular chemistry, (ii) chemical engineering (e.g. equilibrium thermodynamics and transport phenomena), (iii) mining and materials engineering (e.g. mineral processing and extractive metallurgy), and (iv) process and systems engineering.
- In the area of separation materials, there is a critical need to design and synthesize robust, recyclable supramolecular hosts that are capable of selectively extracting critical materials from complex, heterogeneous media that can be highly corrosive and damaging to many available materials. They must be capable of seamless integration with existing separations equipment to be economically viable.
- In the area of separation systems, there is a need for stronger collaborations between chemical engineers and chemists as to better understand the underlying physical and chemical processes that effect design and scale up of separation processes and systems for critical materials. Not all bench-scale processes can be easily scaled up due to technical and economic viability issues.
- Synthetic membranes have become the critical components of a broad range of sustainability applications including: (i) energy generation, conversion and storage (e.g. fuel cells and batteries), (ii) water purification (e.g. desalination and water reuse), and (iii) chemical and biological separations (e.g. gas purification and protein separations). However, the utilization of membrane technology in the extraction, recovery and purification of critical materials from solutions (e.g. mining leach liquors and industrial wastewater) has received limited attention to date. Thus, there is a need for fundamental research in the development of new membranes (e.g. nanofiltration and affinity membranes) for use in the extraction, concentration and purification of critical materials including rare earth elements (REEs) and platinum group metals (PGMs).

- To achieve materials sustainability in clean and renewable energy technologies (e.g. solar photovoltaic cells, wind turbines and electrical vehicles), there is a great need to find alternatives to REEs and PGMs based on earth abundant elements. Breakthrough chemistry and advanced engineering will be necessary to develop alternatives to REEs. The search for alternatives is particularly acute, as supply and demand curves are rapidly approaching unity for such REEs as neodymium (used in the production of wind turbines).
- Currently, the education curriculum in separations science and technology is highly fragmented with students getting educated/trained in different versions/flavors of SEE depending on their major field of studies.
- There is a great need for a new and more unified education curriculum in SEE that integrates basic knowledge of the principles of separations science (e.g. thermodynamics and transport phenomena) and materials (e.g. supramolecular hosts, media and membranes) with engineering knowledge (e.g. unit operations and process/system design) and discussion of the applications of SEE to the global sustainability challenges in energy, water, food, chemicals, materials, clean environment and global climate change. More specific recommendations are given below:
    - Science and engineering curricula needs to comprehensively integrate and emphasize separations science with a focus on sustainability-related applications
    - Science and engineering faculty need to be better prepared to teach “green” courses that are being requested by students. Today’s generation of chemists and engineers focuses much more on “green” economics and sustainability
    - A potential way to get students excited about separation sciences is to illustrate its critical role in the solution of societal challenges in energy, water, food, materials, environment and climate

Introduction and Background

Natural resources derived from the Earth's lithosphere, hydrosphere and biosphere are the building blocks of modern human society, and require judicious use to support a *sustainable* modern society. Like energy and water, the availability of minerals/metals is critical to the world economy, especially since metals are a non-renewable resource. Although the United States (US) is one of the world's largest producers of minerals/metals, it imports more than 70% of its needs for important elements, many of which have been listed as *critical materials* by the U.S. National Research Council[1] (NRC). The NRC published one of the most comprehensive studies of critical materials in 2008[1]. In this seminal study, the NRC identified the conditions that make a material "critical". According to this study, a mineral or material must be both "essential in use" and subject to "supply restriction" to be deemed "critical". The NRC subsequently developed and applied the "criticality matrix" (Figure 1) as a broad framework for assessing the criticality of a given material. In the NRC criticality matrix framework, a specific mineral/material (e.g. mineral A and B) can be placed on Figure 1 "after assessing the impact of restriction on the mineral's supply should it occur (vertical axis) and the likelihood of a supply restriction (horizontal axis)". The degree of criticality of a given mineral/material "increases as one moves from the lower-left to the upper-right corner" of Figure 1.

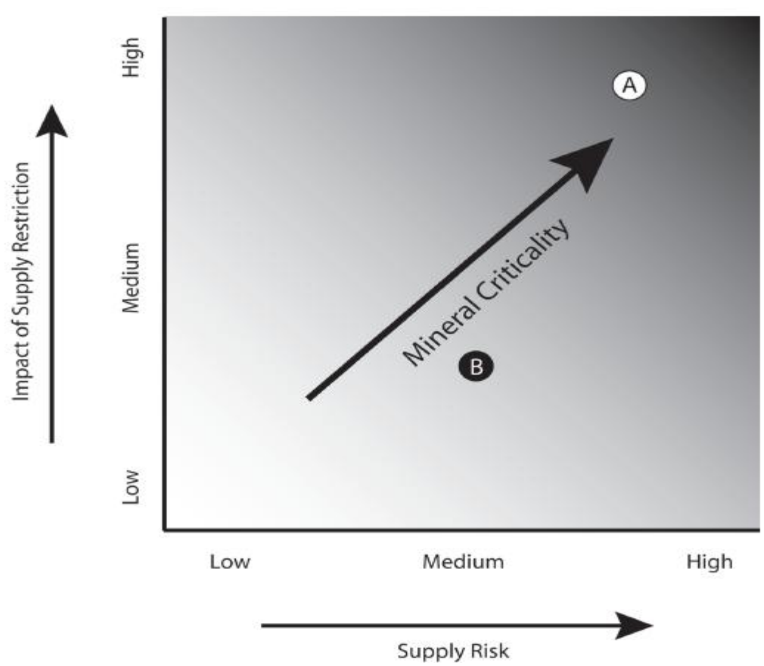

Figure 1: Criticality Matrix Developed by the National Research Council[1]

The NRC subsequently applied the criticality matrix to 11 elements and mineral groups including copper, gallium, indium, lithium, manganese, niobium, tantalum, titanium, vanadium, PGMs (platinum, palladium, rhodium, ruthenium, iridium, and osmium) and REEs (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium). The overall results of the NRC study suggest that the minerals/materials with the "highest degree of criticality at present" include indium, manganese, niobium, PGMs and REEs[1].

Recent stresses in the global market of rare earth elements have brought the sustainable supply of *critical materials* to the forefront in the U.S. and other industrialized countries[2–7]. In addition to REEs and PGMs, significant amounts of copper, silver, gold, manganese, lithium, titanium and gallium will be needed to build the sustainable products, processes, and industries of the 21st century[2–7]. During the last 2 years, the supply and utilization of critical materials in renewable energy technologies has been discussed in numerous symposia, reports and publication[2–14]. To date, only a few symposia and reports have been devoted to the role of SSE in the sustainable extraction, recovery, recycling and replacement of *critical metals* with earth-abundant elements[2,15]. During its recent SusChEM (Sustainable Chemistry, Chemical Engineering, and Materials) symposium[15], the National Science Foundation (NSF) identified research in SSE as a key priority for ensuring a sustainable future.

As a follow-up to the NSF SusChEM symposium, we organized a symposium entitled *"Ensuring the Sustainability of Critical Materials and Alternatives: Addressing the Fundamental Challenges in Separation Science and Engineering"*. This symposium was held on August 21 during the 2012 Fall meeting of the American Chemical Society (ACS) in Philadelphia. This 1-day symposium was jointly sponsored by the American Institute of Chemical Engineers (AIChE) and ACS. The program included contributions from participants in the form of scheduled PowerPoint presentations, Q&A from the audience, and dialogue from the panel discussion following the presentations (see appendices for further details). The primary goal of this symposium was to identify and propose plausible solutions to the primary challenges in the SSE field that are relevant to the sustainability of *critical materials*, an important research area to societal challenges in the near future. Although the symposium was primarily focused on the scientific challenges in SSE and associated technology gaps, issues relevant to recycling of *critical materials*, educational reforms, and ways to develop a sustainable and capable separations workforce were also addressed in the symposium and are captured in this report.

Opportunities and Challenges for Separations Science in the Sustainability of Critical Materials

SSE is a broad discipline that integrates basic scientific and engineering knowledge from many fields including: (i) analytical, physical, inorganic, polymer and supramolecular chemistry, (ii) chemical engineering (e.g. equilibrium thermodynamics and transport phenomena), (iii) mining and materials engineering (e.g. mineral processing and extractive metallurgy), and (iii) process and system design/optimization. SSE plays an essential role in the extraction, isolation, and purification of natural resources, chemicals and essential/critical materials needed to build the generation of sustainable products, technologies and industries of the 21^{st} century. Many current and important applications of SSE (petrochemicals, pharmaceuticals, mining) draw from processes that fall within these aspects of the separations science toolbox. To meet the rapidly expanding demand for critical materials such as REEs and PGMs, considerable advancements in SSE are needed to augment the world's supply from known deposits. It is often staggering to note the amounts of critical materials in the products we use every day. For example, in just one electric vehicle, close to 25kg of REEs are needed[16]. These include La and Ce as components in the nickel-metal hydride (NiMH) battery, Nd, Dy, Pr, and Tb used in the electric motor, and Eu and Ce used for the liquid crystal display (LCD). Even a simple compact fluorescent light bulb requires over a gram of REEs. As technologies advance, so does the need for REEs. A growing middle class and more extensive use of higher technology products ensures sustained pressure on the demand for REEs and other critical materials. What's more, the need for increased domestic REE production is not a future need; many estimate that the demand for REEs is already beyond the production capabilities outside of China, due to China's own need for its vast REE resources, as demonstrated in Figure 2.

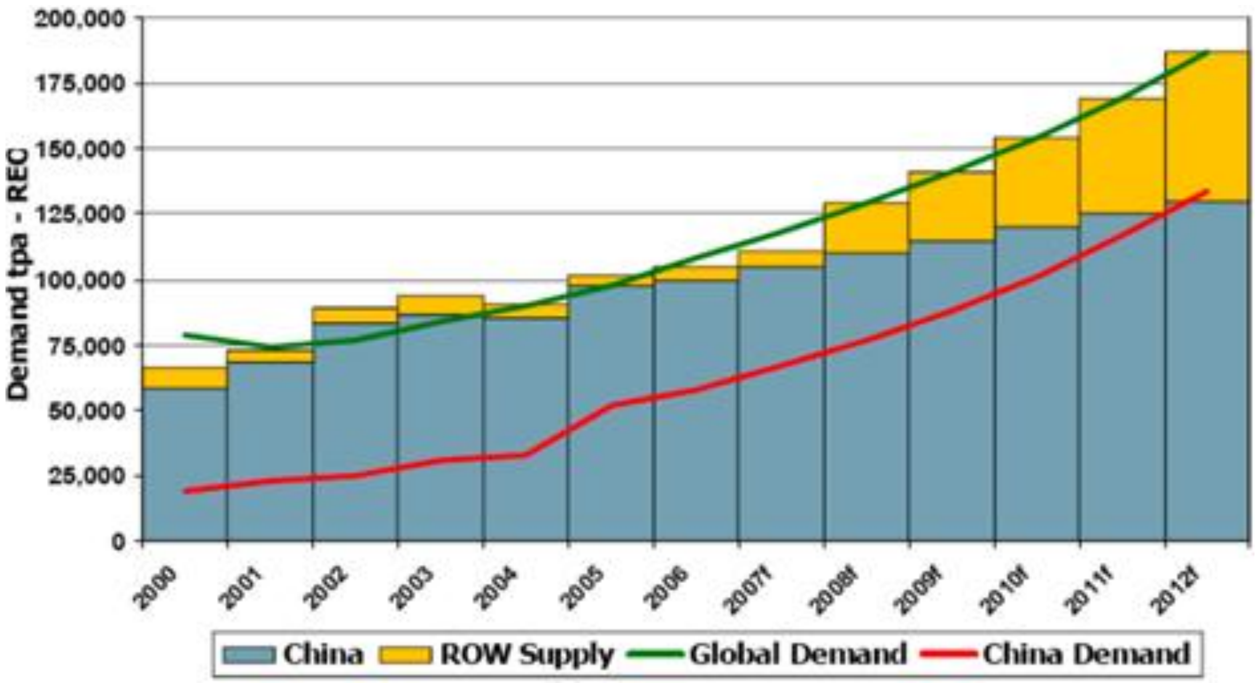

Figure 2: Supply and demand of RE oxides within China and globally[17].

Grand Challenges and Major Knowledge and Technology Gaps

The term REE is in some ways a misnomer: some REEs are no more rare than other commonly mined and "abundant" metals (Figure 3). For example, cerium, lanthanum, yttrium, and neodymium, the most abundant of the REEs, are actually in the Earth's crust in greater quantities than lead. What makes REEs particularly challenging to produce is that they are thinly dispersed within the crust compared (an estimated average concentrations of 200 ppm) to more commonly mined ores and are chemically similar to the much more common Group II elements. This makes separation and processing costs of some of the REEs substantially higher than those associated with the more commonly mined materials. The high cost of processing means metals such as tellurium are recovered as by-products during copper mining rather than being an exclusively obtained resource.

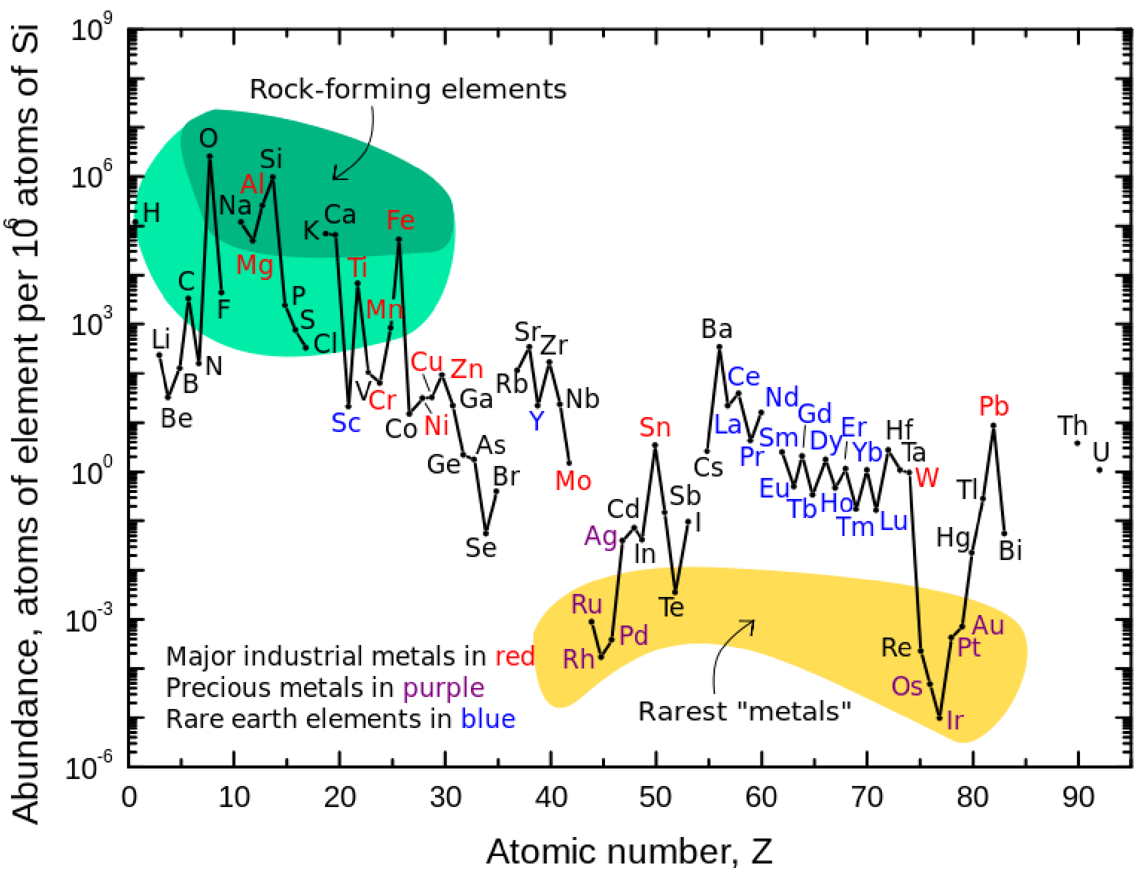

Figure 3: Abundance of REE in the Earth's upper crust[18].

To address the challenges associated with increased REE productions, significant inroads into the development of chemical and engineering separation processes are needed. In particular, "process intensification", integration of separations systems with continuous flow processors, is a potential game-changer, but is currently not in widespread use. Thus, efforts to further develop this area are needed. The continued use of batch-style methods are unsuitable methods for long-term extraction solutions, due to the inherently low throughput. The processes must also satisfy the obviate need of economic viability. A prevalent theme in the symposium was that these requirements necessitate strong collaborations between chemists and chemical engineers to satisfy the underlying physical and chemical processes that are lacking for engineered design and scale-up.

Furthermore, new, highly selective and tunable liquid-liquid extraction agents would be beneficial to the separations field. Precedents have been set for the development of such useful tools. In the purification of cesium ions from complex high-level waste generated during the production of plutonium, a new family of crown ether extractants was capable of achieving decontamination factors of

350,000[19]. New organic extractants selective for heavy metals that can pull desired cations from aqueous media and be "stripped" back into aqueous media in purified form significantly improve the overall REE production process.

Another recurrent theme throughout the symposium was the need for fundamental research in chemistry towards the development of new membranes for use in separations. New membranes could be used to improve many aspects of the concept of sustainability, such as carbon dioxide and hydrogen sulfide capture, in addition to the capture of critical REEs necessary for providing the power needs for the world in coming years through emerging technologies (e.g. solar, wind, batteries). Advances in organic-inorganic hybrids would be useful for combining the separating ability of porous inorganics with the process- and scale-conducive properties of organics, as demonstrated for CO_2 capture by the Nair group at Georgia Tech[20].

A case study of the challenge related to phosphorus production was highlighted during the symposium. The United States Geological Survey notes that, currently, "there is no substitute for phosphorus in agriculture." Given that there is no Haber-Bosch analog to phosphorus production, the continued production of phosphorus represents a grand separations challenge to retain agriculture's ability to sustain the world's growing population. Some estimates suggest that world phosphorus production will peak within one generation, in approximately 2035[21] (Figure 4).

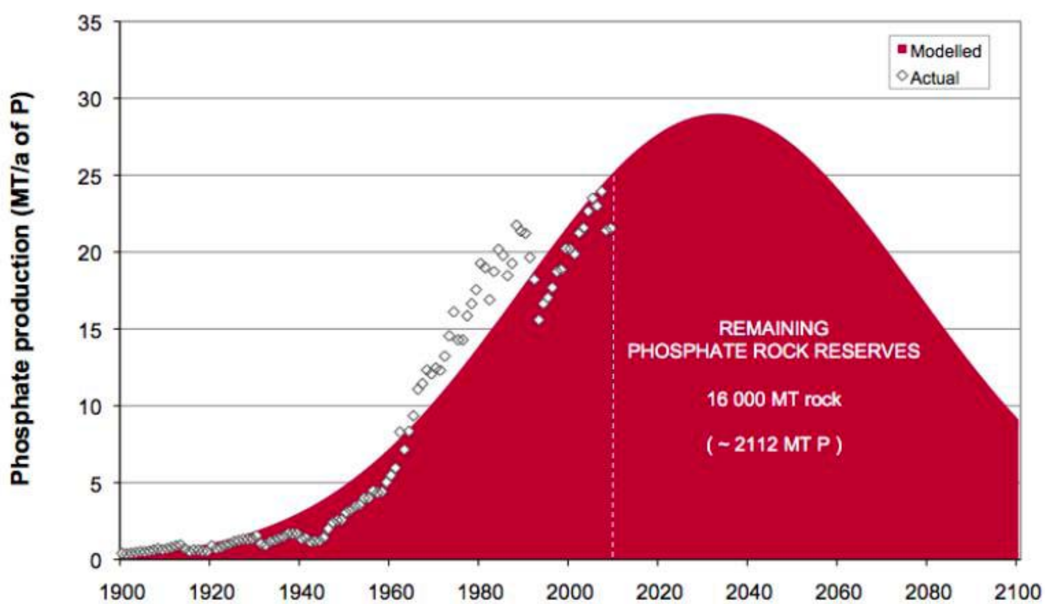

Figure 4: Estimated production of phosphorus[21].

Given that phosphate mining generates other toxic, though sometimes useful metals, such as Cd or Pb, and that only approximately 40% of mined phosphate is recovered from the rock, this represents a tremendous opportunity for separations science to contribute to an essential mining process necessary to sustain basic food crops throughout the world. Alarmingly, current estimates suggest that the majority of the world's supply of phosphorus is confined to a small geographic region of the world outside of the United States[22], further underscoring the obligation for scientists to develop new technologies that will lead to more secure supplies of this critical element. The study by Cordell et al. made an important point regarding this situation that bears repeating for all future separations-related challenges. The authors wrote, "Failure to take a systems approach could result in investment in costly and energy-intensive phosphorus recovery technologies that do not address the whole system and hence do not provide the greatest outcome for sustainability, or at worst, conflict with other related services (such as energy supply)."[21] New technologies that can improve the extraction and separations process are critical to maintaining sustainable production of critical elements.

Recent evidence suggests that REEs reside in fairly high concentrations in Canadian Shale Oil deposits[23], while a similar co-occurrence of hydrocarbons and REEs may be present in the Utica Shale deposit in the Midwestern and Northeastern United States[24], though confirmation is still needed. Thus, opportunities exist for concomitant hydrocarbon and REE extraction and are ripe for separations science innovation. A company called ABS Materials, stemming from work by the Edmiston group at Wooster College, is attempting to do just that with a multi-stage extraction process whereby outer nanopores, using mobile phospholipids that can selectively transfer REEs to chelating groups in interior nanopores, selectively accumulate these minerals for downstream processing and harvesting. Systems like this, along with larger scale systems for extracting REEs in produced water containing high amounts of hydrocarbons, would allow for synergistic production of critical materials, having the added benefit of harvesting the hydrocarbons that exist within these sources.

Ultimately, SSE needs to design and synthesize robust, recyclable separations materials that are capable of selectively extracting critical materials from complex, heterogeneous media that can be highly corrosive and damaging to many available materials (e.g. high acidity and salinity). They must be capable of seamless integration with existing separations equipment, such as packed-bed reactors, pressure vessels, and membrane modules and systems. Effective leveraging of existing separations technologies, including solvent extraction, ion exchange, chromatography, dissolution, crystallization, electrospinning, and pyrometallurgy with emerging technologies such as continuous flow systems, ionic liquid-based solvent extraction, affinity membranes, magnetic separations, and dendrimer enhanced filtration would allow for rapid incorporation of new technologies for more efficient extraction methods.

The Role of Separations in the Recycling of Critical Materials

For primary, relatively abundant metals (e.g. Al, Cu, Fe, Ni), recycling rates were in the 40-90% range during the early part of the 21st century, and have extensive infrastructure to enable their re-use. Somewhat lower rates were observed for the platinum group metals, used for a plethora of catalytic processes, where recycling rates are very application-dependent. In contrast, REEs, and a few other important elements, such as In, Li, and the aforementioned P, had much lower recycling rates, on the order of 1% or less[25] for end-of-life products. Innovations in the separations science are needed for enabling technologies that allow the recovery and extraction of these elements in their product forms, differing substantially from the current extraction processes performed when harvested in their typical ore forms. Recycling these materials in these forms offers the considerable economic advantage of lower input energies to obtain raw materials, and should be aggressively pursued. It is important to note that this advantage is maintained only when the recycled materials can be collected and processed in geographic distributions that require little expenditures in the way of transport energy costs, which is a critical component to consider when designing new separations methods for recycling.

Current Challenges and Progress in the Recycling of Critical Materials

Along with improved production capacity of fertilizing minerals stemming from innovations in separations science, great opportunities exist to retrieve many of the minerals in a re-use capacity in storm water runoff. A large portion of the energy input in commercial agriculture, in some estimates as high as 50% or more, comes from fertilizer (nitrate) production[26]. If new separations membranes or extractants could harness the runoff of energy-intensive nitrates and/or production-limited phosphorus, substantial improvements to resource availability could be obtained. Recent advances by the Edmiston group at Wooster College have demonstrated the ability to reduce nutrients in storm runoff by a silica-based, metal-imbedded absorbent (Osorb® media, http://www.absmaterials.com/osorb). The absorbent is incorporated into strategically-placed bioswales to capture nitrate and phosphate (NP) from storm water via biotic and abiotic processes. Development of specialized absorbents or membranes to recover NP nutrients from agricultural runoff may become economically feasible if prices increase due to scarcity of minerals and energy. NP recycling is highly desired for environmental protection because leaching of these nutrients into bodies of water leads to massive algae blooms and subsequent eutrophication.

During the panel discussion, considerable dialogue was devoted toward ways by which the recycling of critical materials could be improved. Several suggestions related to science and legislative policies were provided. They are summarized as follows:

- Short-term monetary incentives may have a mild impact, but should not be the primary mechanism by which recycling rates of critical materials are achieved
- Communication problems are one reason recycling rates for these types of materials are so low. While it is understood, though not always practiced, to recycle typical consumer goods containing aluminum and plastics, no such knowledge base exists for various REEs and other critical materials. The public is not keenly aware of this problem and very few disclaimers or notices exist on consumer products indicating the need to recycle important elements within devices. Better dissemination of this knowledge is urgently needed.
- The panelists felt that engineering curriculum, as a whole, lacks a strong systems-level approach to engineering new technologies. Heavy emphasis is placed on the technology and the new invention, but very little attention is paid to the full life cycle of product. Recycling of a product should be built in to the product's metrics, and specific goals in those metrics could encourage innovation.
- Along these lines, the panel felt that ultimately, building better products would be necessary, capable of robust use but also amenable to an easy recycling approach when the product's function has ended. Added panelist Mark Johnson, "Invention is a one-way policy arrow." If one can design products amenable to easy, automated recycling processes is one solution to the problem, and likely the most effective one.

Development of Alternatives to Critical Materials

In addition to the improved extraction and separation of critical materials, another important tool in the sustainability agenda is the development of new, abundant, and safe alternatives to the critical materials necessary to maintain a healthy and vibrant economy and society. As an example, if the world wanted to construct 1TW of average photovoltaic (PV) energy using many of the currently available PV materials at 15% efficiency, resource limitations would not support this level of energy production. To circumvent this, innovations are needed that can either utilize earth abundant semiconductors, such as silicon-based photovoltaics, and other S, Cu, Fe, Zn, and P-based alternatives, or significantly improve light absorption while reducing semiconductor volume in PVs containing precious metals. Many such unconventional PV materials could readily supply the world's energy needs if such materials' energy outputs could be significantly enhanced with new research[27]. Furthermore, in many industry-relevant catalytic processes there are also considerable opportunities for platinum group metal (PGM) replacements for those elements that are particularly rare and of limited supplies.

Technological Areas in Need of Alternatives

In 1898, William Crookes said "the fixation of nitrogen is vital to the progress of civilized humanity." At the time, the world's fertilizer for food crops was produced primarily through South American guano farms of finite supply. Within ten years, basic research and an ensuing battle between academic rivals produced one of the more monumental breakthroughs in science; the Haber-Bosch process by which the world's ammonia supply now relies upon for the sustainable production of food crops. Similar innovations in basic chemistry and advanced engineering will be necessary to develop alternative methods of producing elements capable of sustaining the world's population, whether they are related to food production, water treatment, or energy production. REEs are currently the cornerstones of emerging industries in energy and transportation, playing key roles in magnetic systems capable of translating torque efficiently into electricity. For these critical applications, the search for alternatives is particularly acute; supply and demand curves are rapidly approaching for neodymium oxide, an element used in permanent magnets in wind turbines, for example[7].

Many other applications are looking for the requisite disruptive approaches leading to technological change. They include: batteries, phosphors, transparent contacts, oxygen separators, and catalysts. Development of new metrics in these fields, capable of establishing new learning curves and approaches, would also drive forward the current state-of-the-art. For example, solutions to droop loss were also identified as an area of research need for the use of light-emitting diodes (LEDs). Elimination of droop loss, a result of Auger recombination, non-radiative effects, and crystal polarity, would lead to significant inroads on lowering first-lumen costs for LED solid-state lighting systems. The high first-purchase price points associated with these losses currently hinder widespread consumer adoption of solid-state lighting at equivalent luminous efficacies [28]. With innovations in dealing with droop losses, the equivalent cost of lighting for LEDs is expected to reach parity with fluorescent lighting in the near future.

The development of rare earth alternatives in permanent magnets represents a particularly difficult challenge. Hundreds of kilograms of rare earths are currently necessary to create the torque-generating equipment found in off-shore wind turbines. There is a precedent for rapid market-share turnover following innovation in these fields, exemplified by neodymium iron boron magnets in the 1990s[7]. Replacement materials should also address breakthrough technologies that can change many properties of permanent magnets to make them more user-friendly, e.g. with high critical current density superconductors and nanomaterial-enabled third generation high temperature superconductors, as well as novel motor topologies.

Case Study: Nanotechnology and the Sustainable Utilization and Supply of Critical Materials for Clean Energy

Energy is a major challenge of the 21st century, and meeting the world's growing demand for energy while significantly reducing CO_2 emissions will require the deployment of orders of magnitude more clean energy systems than what is in place now[5,29,30]. There is a growing realization, however, that the implementation of clean energy systems will require sizeable amounts of technology metals including *critical materials* such REEs and PGMs. In order to address the critical nature of technology metals, it is important to understand the nature of their criticality. Clean technologies require metals such dysprosium and platinum due to some unique functionality that each of these metals provides including superior magnetic, optical, electronic and catalytic properties[5,29,30]. Nanotechnology provides unprecedented opportunities to address materials criticality in clean and renewable energy technologies. Nanomaterials are particularly attractive as functional materials for clean and renewable energy systems due their large surface areas and size and shape-dependent optical, electronic, magnetic and catalytic properties[29,30]. Thus, nanomaterials based on non-critical *materials* and earth-abundant elements are increasingly being optimized and evaluated as components and building blocks of energy generation, conversion and storage systems[29,30]. The most promising applications of nanostructured materials in clean energy technologies include: (i) solar cells, (ii) wind turbines, (iii) electric vehicles, (iv) batteries, (v) energy-efficient lighting devices, and (vi) solar fuel generation[29,30].

Nanotechnology can also help augment the supply of critical materials for clean energy technologies[29]. In aqueous and mining leaching solutions, critical metals can exist as cationic or anionic species depending on solution composition, temperature and pH. Critical metals that are often present as cationic species in aqueous solutions include REEs, copper, nickel, cobalt and lithium[29]. Critical metals that predominantly form anionic species in aqueous solutions include platinum, gold and oxyanions of various important metals including molybdenum, vanadium, tungsten and germanium[29]. Advances in dendrimer nanotechnology are providing new opportunities to design and synthesize dendritic nanoscale hosts with high capacity/selectivity and tunable size and chemistry that can efficiently extract anions or cations from solutions using low-pressure membrane filtration[31–34]. Dendritic nanomaterials can be processed into various form factors including particles, fibers and membranes, thus providing new opportunities to develop more efficient separation materials and processes for the selective recovery of critical metals from non-traditional sources including mine tailings, industrial wastewater and electronic wastes with minimum environmental impact[9–11,27,29]. Although nanotechnology has great potential to help improve or achieve materials sustainability for clean energy technologies[29], a key challenge will be to process and integrate nanomaterials into engineered systems with demonstrated added values. Moreover, it is important to keep in mind that clean energy technologies are materials intensive, and that criticality is not a fixed property of a material[5,29,30]. Thus, scientists, engineers and policy makers need to adopt a holistic approach to achieve materials sustainability in clean energy technologies. This will include (i) materials substitution and/or system design to reduce or eliminate criticality, (ii) recycling, (iii) improvements in metal extraction efficiency and yields from existing mines and (iv) recovery from non-traditional sources such as mine tailings, industrial wastewater and electronic wastes[5,29,30]. We expect that separations science and engineering (SSE) to continue to play a key role in achieving materials sustainability in clean energy technologies[29].

Educational and Workforce-Related Challenges

Throughout the symposium, considerable efforts were made to address the fundamental education and workforce-related challenges that are relevant to separations science and engineering. A synopsis of these discussions is included first, and is followed by the dialogue devoted to education during the panel discussion.

Academic challenges specific to separations sciences were identified. A steady decline in majors related to separations science and engineering, such as mining and extractive metallurgy has occurred over the last few decades[5] (Figure 5).

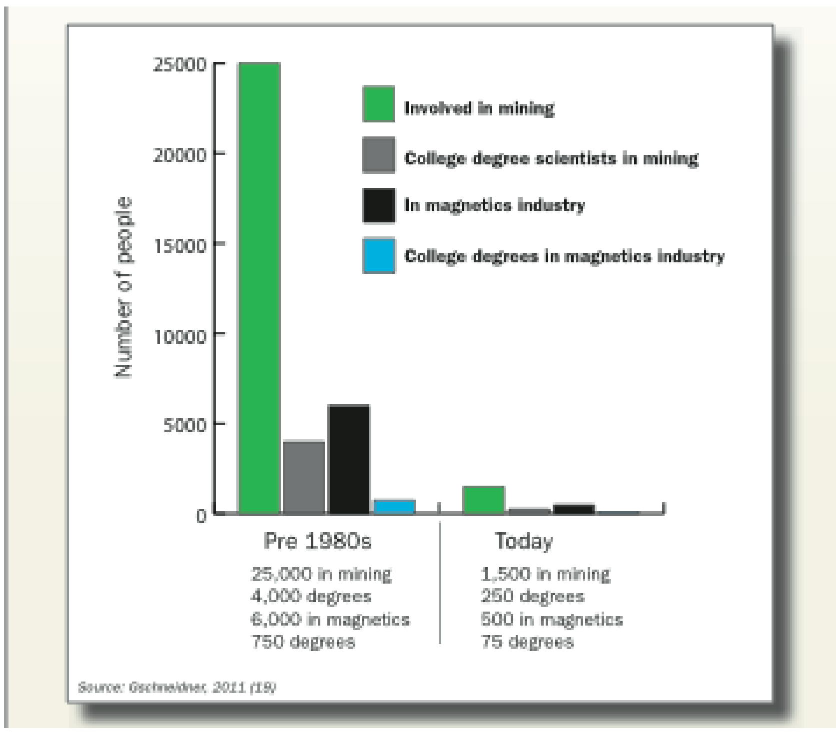

Figure 5: Decline in training of U.S. students for separations-related disciplines[5].

There is a considerable need to recruit and train the next generation of separations scientists. Ideas to recruit and retain students in these fields were discussed in more detail during the moderated panel. Participants in the symposium also identified another key theme regarding the education of separations science; separations science now lacks a "home." Currently, the education curriculum in separations science and technology is highly fragmented with students getting educated and trained in different versions of SSE depending on their major fields of studies. For example, the SSE curriculum in most chemistry departments focuses on analytical and preparative chemistry. In contrast, most chemical engineering departments focus on unit operations and process design; whereas mining/materials departments focus on mineral processing and metal extraction/purification (e.g. mineral processing, hydrometallurgy and pyrometallurgy). Thus, there is a great need for a new and more unified education curriculum in SEE that integrates basic knowledge of the principles of separations science (e.g. thermodynamics and transport phenomena) and materials (e.g. supramolecular hosts, media and membranes) with engineering knowledge (e.g. unit operations and process/system design) and discussion of the applications of SSE to the global sustainability challenges in SusChEM. More to the point, the participants believe that integrated curriculum could improve interest in SSE. To achieve this integration is not to simply add additional courses but rather to add the "lens of sustainability" to curricula for both majors and non-majors[35]. This could be done by explicitly including examples of major technological and societal challenges that were solved using SSE. For example, deconstructing an iPhone and quantifying the value of the metals within it will add relevance and immediacy[36]. Doing this in the context of systems thinking, asking how we could use these metals from cradle to cradle, doing a life cycle assessment, would *not only* add the lens of sustainability *but also* enroll the students in the solution. In industry, new hires entering the workforce also often do not fully understand the role of separations in the production process, and the economic benefits must be taught on site. There are clear avenues for addressing and improving the understanding of separations and their role in the supply of critical materials for students of all ages - from K to Gray; content development will be key.

A parallel and recurring theme during presentations of the symposium was the idea that during the undergraduate education, students should be exposed to the *idea* of sustainability in every aspect that they live, not just in their professions, but also as a way of life. This includes not just SSE majors, but all majors that play a role in a sustainable future, which one could argue might include all majors. Collaboration across disciplines, from the hard sciences to the humanities, would encourage this type of thinking and innovation. An educated populace cognizant of these issues would be better prepared to consider solutions to these problems. Specific suggestions for this type of training should include (i) curriculum incorporating case studies related to economic and safety analyses, (ii) life-cycle and material flow analyses, (iii) exposure to industrial research and design with real-world constraints, (iv) mandatory reflection on product scalability, material availability, product lifetime, and recycling capabilities, and (v) emphasis on communication skills with stakeholders, including the lay public. It was encouraged to include sustainability as part of the degree accreditation process.

The panel discussion identified several potential suggestions to address the deficiencies related to the educational aspects of separations science. The question posed to the panel was framed in this way: How do we educate for sustainability and for a separations curriculum, given the already burdened course loads in the engineering curricula?

- Some of the faculty noted that the there already seemed to be an increased interest in separations science by today's students. It was suggested during the panel that the faculty need to respond to this interest by creating and modifying curricula and degree programs as needed. Indication of the renewed interest of separations science, as it pertains to new energy technologies, is exemplified by the student-led initiative at the Massachusetts Institute of Technology. The panel also noted that faculty at engineering schools are often behind on the relevant policy and economic issues implicit in these programs, and can thus be another area for improvement to drive further successes in separations science.
- Extending and expanding student participation, *e.g.* through internships, to National Laboratories would also play a positive role in promoting the role of separations science in academic institutes.
- The overall educational structure is changing, and it is also the responsibility of students to help "train" faculty to perform the kind of classroom learning the students' desire. For example, at MIT, students recently requested a "green" energy course. However, not all faculty throughout the nation were individually equipped to conduct such a course, requiring knowledge of science, technology, and economics outside the scope of any individual faculty's area of expertise. In these cases, it is a collaborative effort guided by student input that could lead to these types of courses intended to create the next generation of cutting-edge separations scientists capable of systems-level and lifecycle analyses related to product and application development. This latter goal can also be highly developed with closer student collaboration with industrial scientists in internship programs, where science and application intersect. Dow Chemical has sustained programs encouraging these collaborations, and it is likely that more such programs would further enhance the educational experience of engineering undergraduates.
- When the panel was asked about teaching of lifecycle analysis, and whether it is possible to do so now, the response was that this knowledge already exists, particularly within industry, and could serve as a potential source for assistance with faculty. An example includes the elimination of the use of plastic bags in the city of San Francisco, due the results of studies

examining the impact from production to waste of these materials. It was felt that these principles need to be disseminated to other faculty throughout the nation who may lack the institutional resources and breadth of faculty to create the material on their own.

- An additional mechanism by which one could enhance the training of students in separations would be to incorporate a unifying grand challenge for the community, such as coming up with a strategy for separating the difficult to resolve lanthanides, which have similar sizes and reduction potentials. A breakthrough in this particular problem could have dramatic impacts for the recognition of this field in critical materials sustainability.

Outlook

- Continue the discussion with another symposium co-located with the AIChE Spring Meeting.
- Look for other appropriate partnering organizations that can contribute to the discussion. For example, consider inviting the North American Membrane Society to offer the attendees insights on current and future membrane separations technology that impact critical materials.
- Initiate a task force consisting of leading scientists and engineers from academia, industry, US national laboratories to revamp and upgrade the curriculum in SSE to recruit and educate the next generation of scientists and engineers to tackle challenging separation problems in SusChEM.
- Continue involvement with appropriate ACS groups and involve AIChE's Center for Energy Initiatives (CEI) and Institute for Sustainability (IfS).

Appendices

Appendix A - References

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Appendix B – Symposium Participants

Symposium participants included a diverse interdisciplinary group of scientists with a wide range of expertise and National Science Foundation observers.

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Appendix C – Symposium Schedule

The symposium used presentations to stimulate discussions and collaborations on symposium recommendations.

Tuesday, August 21st

Morning Schedule

Catherine Hunt **8:00 – 8:30** to discuss Setting the Stage for Sustainability

Tanja Pietrass **8:10 – 8:20** to discuss Separation Science for a Sustainable Future

Mark Johnson **8:20 – 8:30** to discuss Developments in Alternatives to Critical Materials for Energy Applications

Harry Atwater **9:00 – 9:20** to discuss Finding Alternatives to Critical Materials in Photovoltaics and Catalysis Part I: Academic Perspective

James Stevens **9:20 – 9:40** to discuss Finding Alternatives to Critical Materials in Photovoltaics and Catalysis Part II: Industrial Perspective

Andy Davis **10:00 – 10:30** to discuss Meeting the Global Rare Earth Challenge: Molycorp from Mine-to-Magnets

Paul Edmiston **10:30 – 11:00** to discuss Extractions of Dissolved Organics and Metals

Susannah Scott **11:00 – 11:30** to discuss Findings and Opportunities from the 2012 NSF SusChEM Symposium

Catherine Hunt **11:30 – 12:00** to end AM session with concluding remarks

Afternoon Schedule

Mamadou Diallo **2:00 – 2:10** to discuss Sustainable Supply of Critical Materials: Addressing the Fundamental Challenges in Separation Science & Engineering

Bruce Moyer **2:10 – 2:50** to discuss Sustainable Extraction of Critical Metals from Saline Water and Industrial Wastewater: Challenges & Opportunities

Robin Rogers **2:50 – 3:10** to discuss Ionic Liquids and Strategic Metals: Challenges & Opportunities

Moderated Panel: Rethinking the Role of Separation Science & Engineering - Reduce, Recycle, Repurpose! **3:50 – 4:50**

Hunt (moderator), Johnson, Moyer, Rogers, Atwater, Stevens

Lin He and Rosemarie Wesson **4:50 – 5:00** to end with concluding remarks

Appendix D – PowerPoint Contributions

Participants were asked to provide presentations focused on critical materials and their sustainable extraction, recovery, and purification.

Power-point slides contributed by symposium participants can be downloaded from the Critical Materials Symposium website at http://criticalmaterials.aiche.org/.