Testimony of

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Before the
Subcommittee on Energy
of the
Committee on Science, Space, and Technology
U.S. House of Representatives

Research and Innovation to Address the Critical Materials Challenge

December 10, 2019

Chairman Lamb, Ranking Member Weber, and Members of the Subcommittee, thank you for the opportunity to discuss the importance of research and innovation to address the critical materials challenge, and thank you for your continued strong support of physical sciences and energy research. I am Adam Schwartz, Director of Ames Laboratory, a Department of Energy National Laboratory located on the campus of Iowa State University in Ames, Iowa. Ames Laboratory is a single program Office of Science Laboratory with the mission to create materials, inspire minds to solve problems, and address global challenges. I am also a professor of Materials Science and Engineering at Iowa State University. Before arriving at Ames Laboratory five years ago, I spent nearly 23 years at Lawrence Livermore National Laboratory, a National Nuclear Security Administration National Laboratory in Livermore, CA.

The United States is the world leader in physics, chemistry, and materials research. Core materials science research, supported by both the Department of Energy and the National Science Foundation, has created an innovation system that is unmatched anywhere in the world. This innovation eco-system has allowed our nation to transform fundamental understanding of the chemistry and physics of materials into technologies that enhance our economic security, energy security, national security, and our quality of life. From computers and cell phones to wind turbines and electric vehicles, to key defense systems, our country has reaped tremendous benefits because of decades of Federal investment in academia, national laboratories, and scientific user facilities. To remain a world-leader in these crucial security areas, the United States must continue to innovate with new materials, new products, new energy options, and new defense applications.

At the heart of most technological advances are sophisticated, engineered materials carefully designed to provide desired functions that exploit the unique characteristics of chemical elements. Early cell phones in the 1980s consisted of materials that used approximately 30 elements from the periodic table. Today's smart phones contain 60-70 different elements, each one performing a very specific function. New technologies and engineered materials create the potential for rapid increases in demand for some elements that until now have only been needed in small quantities.

What are critical materials and why are they so critical?

A critical material provides essential functionality to a modern, engineered material, has few ready substitutes and is subject to supply-chain risk. In the short-to-medium term (a year or two, up to about a decade), these risks may be due to unexpected demand growth that overwhelms existing production capacity or otherwise risky supply chains due to lack of supply diversity, geopolitical risks, or other factors. In the long term (more than a decade), risks may be due to geological scarcity of resources, lack of efficient and non-polluting production technologies, insufficient human capital, or insufficient investment.

Exactly what is "at risk" depends on the circumstance. To a single company or a sector of the economy (such as manufacturing), production, employment, and profits are at risk if supply chains are insecure; additionally, a company's reputation may be at risk if it relies on sources of production that damage the environment. The natural environment may be at risk if existing production technologies significantly degrade human health or ecosystems as part of producing a critical material. The development and deployment of desirable new technologies (such as electric vehicles) may be at risk if materials scientists and engineers avoid using a specific material providing the best functional properties because of fear the material will be unavailable in sufficient quantities at prices customers are willing to pay.

A recent example of materials criticality occurred in 2010, when the prices of materials based on the rare-earth elements spiked, in some cases rising to 25 times their prior values. While rare-earth elements are typically used in relatively small quantities, they are functionally essential, and presently irreplaceable in a wide range of industries, including the production of clean energy technologies. The most prominent examples – although by no means the only – are two of the rare-earth elements, neodymium and dysprosium, used in permanent magnets for electronics, high-efficiency motors, the most energy-efficient wind turbines, and key defense systems. To address the rare-earth supply challenges, the United States, Japan, the European Union, and others responded to the spike in rare-earth prices through various approaches. The U.S. Department of Energy's 2011 Critical Materials Strategy outlined a three-pronged approach to supply-chain shortfalls:

- Achieve globally diverse supplies: A major factor causing criticality is the concentration or location of supply in a single company, country, or region.
- Identify appropriate substitutes: For example, develop substitutes for materials like magnets or phosphors that use little or none of the critical elements.
- Improve capacity for recycling, reuse, and more efficient use of critical materials: Minimizing the draw-down of existing supplies by improving manufacturing efficiency and enhancing recycling and re-use.

As with most things we don't have enough of, the choices are to make more or use less.

To implement this strategy, DOE competed an Energy Innovation Hub and established the Critical Materials Institute in 2013, led by Ames Laboratory. The Critical Materials Institute, or CMI, closely follows the DOE strategy to make more by diversifying supply and improving reuse and recycling, or use less by developing substitutes. Its work focused initially on the rare-earth elements, but its methods and approaches have been extended to include lithium and cobalt for batteries and gallium, indium, and tellurium in thin-film solar and LED panels.

Before I describe current research efforts and the lessons learned, I want to take a moment to look forward to where new science and technology are required and where advances will lead our nation. World population continues to grow as does the middle class. These global factors will place an even greater stress on diversification of mineral resources, the importance of innovation in creating substitute materials, and the development of the science to improve the economics of reuse and recycling. As our science and innovation engine turns its focus toward quantum information systems, strategies known to mitigate supply chain risks – diversification of supply, materials substitution, and efficient manufacturing and recycling – must be incorporated into research and development efforts. Other important advances in energy research include higher efficiency energy power plants based on new materials designed to withstand harsh service environments, next-generation energy storage to facilitate widespread adoption of electric mobility and the deployment of clean energy technologies, and the revolutionary conversion of refrigeration from 100-year-old vapor compression technology to high efficiency solid-state cooling. All of these advanced energy technologies will require robust and resilient supply chains integrated across the materials lifecycle from source to final product and end-of-life.

Critical Materials Research and Development Efforts

Ames Laboratory, other DOE National Laboratories, and universities were studying critical materials well before they were defined as "critical." It is important to remember that current research, recent success, and all future options are based on years, or decades, of prior research. DOE supports fundamental scientific research through the Basic Energy Sciences program within the Office of Science. Core research in fundamental physics, chemistry, and materials provide foundational understanding for first principles predictions of highly complex materials, separations science (the science of extracting one element from another), and the discovery of new materials with enhanced functionality. This core research establishes the scientific knowledge upon which solutions to technological barriers along entire supply chains are based. In addition, investment in world-class research tools like x-ray synchrotrons, neutron scattering facilities, and leadership-class computers and algorithms have all set the stage for the materials advances and the resulting energy independence that this nation now enjoys. The sustained investment in the National Laboratories and academia coupled with unparalleled scientific user facilities has created the flexible platform on which the nation is addressing the challenge of materials criticality.

There are two substantial DOE programs currently addressing the criticality of rare-earth elements: the Critical Materials Institute, a DOE Energy Innovation Hub funded by the Office of Energy Efficiency and Renewable Energy, and the Feasibility of Recovering Rare-Earth Elements Program, funded by the Office of Fossil Energy and the National Energy Technology Laboratory (NETL).

The Office of Fossil Energy and NETL initiated the Feasibility of Recovering Rare-Earth Elements Program in 2014 in response to the Congressional request for understanding the technical and economic feasibility of extracting and recovering rare-earth elements from coal and coal by-products. The program consists of projects ranging from fundamental research efforts to the design, construction, and operation of small pilot-scale facilities, producing salable, high purity, rare-earth oxides. To date, in conjunction with NETL, approximately 25-30 projects have been actively conducted at universities, National Laboratories, and small businesses, using 300 part-per-million rare-earth-containing coal-based materials such as coal, coal refuse from preparation plants, power generation ash, clay and shale over/under-burden materials, as well as acid mine drainage (AMD) and sludge.

Numerous technical insights and innovations have resulted since this effort began. As examples,

- Nearly 100% of the rare earth content contained in coal-based acid mine drainage can be easily removed, producing extracts that are enriched with higher heavy rare-earth element concentrations in comparison to rare earths produced from other coal-based materials.
- Identification that approximately 80-95% of the rare earth content in lignite coals is in organically associated phases, which are easily extractable, and perhaps comparable to that of rare-earth elements produced from off-shore ion exchangeable clays.
- Development of fiber optic sensors that are capable of detecting *in-situ* part-per-million concentrations of rare earths in liquidus media.

Currently, DOE-NETL has three domestic, first-of-a-kind, mixed rare earth oxide pilot-scale facilities operating, producing small quantities of high purity (maximum 80-90%) rare earth oxides from coal refuse from central Appalachian and Illinois coal basin materials, from northern and central Appalachian acid mine drainage, and from power generation ash produced from eastern Kentucky coals – all turning coal waste materials into potentially remediated and valuable revenue streams.

For the near future, DOE-NETL's efforts will continue to be focused on

- Improving the efficiency and optimization of current rare earth extraction processes, enhancing rare earth extraction and recovery system economics.
- Recovering critical minerals and materials during production of rare earths from domestic coal-based resources.

- Accelerating process scale-up from small pilot to near commercial facilities, that potentially could incorporate advanced, transformational, rare earth extraction and separation processes.
- Producing high purity, individually separated, salable, rare earth oxides from domestic coal-based feedstock materials.
- Continuing development of metallization processes that convert rare earth oxides into rare earth metals for alloying.

The second major thrust to reduce criticality comes from the DOE Energy Efficiency and Renewable Energy’s Advanced Manufacturing Office.

The Critical Materials Institute is conducting early-stage research to accelerate the development and application of solutions to critical materials challenges – enabling innovation in U.S. manufacturing and enhancing U.S. energy security (https://cmi.ameslab.gov/). The team is comprised of four National Laboratories, nine universities, and 15 industrial partners. There are 22 industry, academic, and government affiliate members. CMI has the structure and the connectivity to access facilities and researchers from the Office of Science and EERE as needed.

Rare-earth elements are the most prominent of the critical materials today. CMI aims to develop economically viable processing techniques for improved availability of critical materials for clean-energy technologies, develop new techniques to recover them from waste and scrap, and find acceptable alternatives for use in devices such as generators, motors, lighting, and magnets.

Based on early-stage foundational research, CMI has filed 129 invention disclosures, leading to 58 U.S. patent applications and 12 awarded patents that address rare earth separations for primary metal refining or recycling processes and new magnet compositions and processes.

Diversifying Supply

CMI research to diversity supply aims to increase the supply of critical materials by creating more cost-effective and energy efficient methods for the extraction, separation, and conversion of ore to metal. Generally grouped together as upstream activities, research has focused on developing co-production from existing domestic productions sources. These sources include primary mineral operations such as copper, phosphates, and borax. Advances in computational designs of separation chemistry with enhanced elemental selectivity and improvements in membrane separation has been most effective in reducing processing steps that lower both capital expenditures and operational costs.

Although rare-earth elements remain high on the list of critical materials, the push toward electric mobility increases the demand for energy storage elements like lithium, cobalt, and graphite. CMI is addressing these critical elements as well. Efforts have resulted in new lithium capture technologies for a domestic lithium supply. While the U.S. possesses plentiful lithium resources to not only become self-sufficient in supplying its own needs for battery production, but also to become a net exporter, its current output is small compared to overall global production. Research results obtained by CMI and its partners have led to technologies that can allow domestic production from two novel sources of lithium: geothermal brine and mining tailings. CMI's technologies include a new sorbent that can extract lithium at only several hundred ppm from geothermal brine, a membrane-based method for concentrating the recovered lithium so that a solid lithium product can be obtained, and a new solvent extraction method that can pull impurities out of lithium solutions to produce battery-grade lithium.

Diversifying supply research has also yielded a breakthrough in the economics of synthetic graphite production. Graphite is, along with lithium and cobalt, one of the critical materials used for the production of batteries needed for electric vehicles and grid storage. Unfortunately, graphite is costly to produce from plentiful sources of amorphous carbon such as coal and biomass. Recently, CMI researchers, discovered a way to reduce the processing temperatures from 3100°C to 800°C through electrolysis in a molten salt. This process lowers the energy consumption 90%, shortens the time from days to hours, and leads to potential cost reductions of 50%. Several U.S. companies have already indicated an interest in licensing opportunities.

<u>Reuse and Recycling</u>

Dysprosium, a particularly critical rare-earth element is added in small quantities to improve high temperature performance of rare-earth magnets. CMI scientists developed a new separation technology based on membrane solvent extraction that efficiently and economically separates dysprosium from mixed rare earth solutions, with significantly reduced amounts of acid than conventional methods. This technology has recently been granted a U.S. patent and licensed by Momentum Technologies, a U.S. start-up company that is commercializing an earlier CMI technology for creating high purity mixed rare-earth solutions.

A key step in transforming recycled rare-earth magnets into feedstock for new rare-earth magnets is converting the separated rare-earth oxides into metal. Researchers have developed a commercially viable technology with low environmental impact for reduction of rare-earth oxides into metal. Detailed techno-economic analyses at the earliest stages of research helped the researchers identify and eliminate economic and environmental barriers before significant resources were invested in development of less-than-optimal technologies.

The CMI team has also developed an innovative acid-free dissolution and separation process for removing rare-earth ions from shredded hard disk drives. This process won an R&D 100 award and a Notable Technology Development Award from the Federal Laboratory Consortium.

Developing Substitutes

CMI research in developing substitutes provides alternative choices to usage of the critical materials. Often believed to be drop-in replacement materials, substitution can also be process for process, device for device, or system level substitutions. CMI has developed new materials and processes for both lighting and permanent magnets. The team has discovered suitable green and red lamp phosphor substitutes, reducing the use of the rare earth terbium by 90% and eliminating the use of the rare earth lanthanum for green phosphors, and eliminating the use of rare earths europium and yttrium in red phosphors. Industry is currently assessing the feasibility for commercial lighting via full manufacturing trials. New permanent magnets formulations containing less or no critical elements have been discovered including a formulation that replaces half the Nd in $Nd_2Fe_{14}B$ with lanthanum (La). Since La is a main component in rare earth ore and generally exceeds the amount of Nd, addition of La does not require additional processing, effectively doubling magnet product per tonne of ore. Another new magnet is a "gap magnet" containing no critical elements that will replace rare earth magnets in certain applications where currently only rare earth magnets are in use. Finally, CMI is using advanced manufacturing to print magnets that can triple magnetic performance of low-grade rare-earth magnets, effectively reducing the amount of critical materials needed for a given application.

An Integrated Research Model

An integrated research model coordinating early and later stage R&D that couples fundamental science with scale-up demonstration and commercialization is required to address the full spectrum of R&D needs over the entire supply chain. Cross-cutting fundamental research efforts produce basic knowledge, information, or tools that are of specific value to the applied research, development, and demonstration (RD&D) projects. These types of projects generally do not produce intellectual property and are characterized by very low technology readiness levels. Research outcomes from this type of work are generally published in the open literature and made available through the usual means. As RD&D efforts proceed to higher readiness levels, interactions with the private sector become increasingly more important.

For one example, in pursuit of new magnet materials to replace neodymium-iron-boron, CMI has adopted an approach that includes computer simulations, experimental exploration of candidate alloy compositions using combinatoric methods, and rapid analysis and testing. These methods are each founded in tools previously developed in academia and National Laboratories but they have been advanced and made specifically useful in addressing critical materials. Among many other advances of this kind, CMI has:

- Developed the first successful computer model for predicting magneto-crystalline anisotropy in proposed new materials – an essential contribution from fundamental condensed matter physics in support of developing new magnet materials.
- Developed a new tool, based on additive manufacturing technologies, which allows for the rapid production of target magnet compositions at manufacturing scale. This tool along with the two below, was used to validate the computer code described above.
- Added new capabilities for rapid structural and chemical analysis of materials that take advantage of the additive manufacturing tool described above.
- Added high-throughput magnetic testing capabilities.

All of these capabilities work with each other to address the challenge of critical materials, but they also enhance the capabilities of other Office of Science and AMO programs. Bringing together capabilities across all of CMI’s participating institutions, across a wide spectrum of basic and applied research, CMI has created a range of candidate materials for new high-performance magnets.

While it is conceivable that these advances could have been made without the existence of CMI, under the usual operating procedures, even this simple case would have required traditional funding through four separate projects to develop the tools, and then a fifth funded program to work on the desired material. It has been our observation that progress toward our goal of technology adoption is accelerated – often very considerably – when industry input is obtained early and often during early-stage research efforts. Interactions with industry allow for and promote increasingly intense collaborations as an R&D effort moves from early stage toward demonstration.

Summary and Conclusions

No single institution has all the expertise to solve the full range of critical materials challenges. Large teams, like the Energy Innovation Hubs, bring together expertise from around the country. In addition to all the successes and options that CMI has produced, the most important of all is the enduring capability that CMI has created. It is the combination of criticality assessments, techno-economic analyses, roadmapping, and early input from industry that sets the stage for efficient and effective research into solving critical materials challenges. CMI accelerates the development and application of solutions to emerging or existing critical materials challenges for the benefit of U.S. manufacturing and the global clean energy economy. CMI's critical materials framework integrates expertise across the supply chains to deliver industrially-relevant technologies to diversify supply, improve reuse and recycling, and develop substitutes – both informed and enabled by foundational science.

It is this enduring capability and collaboration that puts the U.S. in the strongest position as new materials become critical and is why CMI in particular is such an important national resource for addressing these challenges that are only going to grow more pronounced over time.

Dr. Adam J. Schwartz is Director of Ames Laboratory, a Department of Energy National Laboratory located on the campus of Iowa State University in Ames, Iowa. He is also a professor of Materials Science and Engineering in the College of Engineering at Iowa State University. Ames Laboratory is a single program Office of Science laboratory with the mission to create materials, inspire minds to solve problems, and address global challenges. Prior to joining Ames Laboratory in 2014, he had nearly 23 years of materials science research and management experience at Lawrence Livermore National Laboratory in Livermore, CA that spanned physical metallurgy to condensed matter physics with a particular focus on phase transformations, phase stability, and electronic structure of actinides and lanthanides. He held leadership positions for Plutonium Aging, Dynamic Properties of Materials, and Physics and Engineering Models programs. He led the Lawrence Livermore National Laboratory team during the development of the Critical Materials Energy Innovation Hub then continued on as the Developing Substitutes Focus Area Leader. In this role, he leveraged his expertise in metallurgy, condensed matter physics, and technical management to drive the innovation of substitute materials. Dr. Schwartz has authored over 100 journal articles, monographs, book chapters, technical reports and co-edited two editions of *Electron Backscatter Diffraction in Materials Science* (Kluwer Academic/Plenum Publishers, 2000; Springer, 2009). Dr. Schwartz holds B.S. and M.S. degrees in Metallurgical Engineering and a Ph.D. degree in Materials Science and Engineering from University of Pittsburgh.