Critical Materials Institute
AN ENERGY INNOVATION HUB

CRITICAL MATERIALS MUSEUM DISPLAY
STATUS AND "HOW-TO" REPORT NO. 3
09-01-2016

This report is the third and final "How-to" report, which includes an update of progress and a review of lessons learned for the Critical Materials Museum Exhibit at Colorado School of Mines (CSM). The first report explained the beginnings of the exhibit, including the inception, purpose, design foundations, and challenges and advantages of the project (available at https://cmi.ameslab.gov/resources/public/cmi-museum-display-report-1). The second report discussed the logistics of the design and acquisition process, with suggestions and anecdotes from this exhibit project (available at https://cmi.ameslab.gov/resources/public/cmi-museum-display-report-2). Topics discussed in the second report included exhibit purpose, location, communication of ideas, budgeting, and resource suggestions for display components. This third report ties all the reports together with additional insights and final exhibit information. The intention for these collective reports is that they serve as a resource for exhibit designers, planners, and builders venturing into the realm of critical materials.

Team expertise is very important, and we certainly could not have built this exhibit without the expertise of our team, donors, expert contributors, and volunteers. As an appendix to this report, you will find a list of all who have made this exhibit possible, including donors, volunteers, and partners (Appendix A). Additionally, a second appendix is included with a list of resources for this exhibit, including mineral specimen vendors, museum case vendors, chemical supply sources, and consumer product resources (Appendix B). This resource list also includes costs (when available) of all purchased and donated items. A third appendix is included with additional resources for exhibit building which were found during the development of this project (Appendix C).

Exhibit News

Opening and Dedication Receptions

Since the second "How-to" report, the exhibit has "gone-live". All materials were on display in the cases for the campus-wide "soft" opening on December 9, 2015. For the grand opening on February 3, 2016, exhibit additions included a video display and phosphor viewing box. The grand opening was held in conjunction with a Critical Materials Institute (CMI) Winter Meeting at CSM. During the grand opening, Dr. Alex King, CMI director, and Dr. Rod Eggert, CMI

deputy director, presented the exhibit to the CSM Geology Museum as a permanent exhibit/gift. The exhibit was received by Dr. Paul Johnson, CSM president, and Dr. Bruce Geller, CSM Geology Museum director (Fig. 1).

Figure 1. Left to Right: CMI Deputy Director and CSM Professor Dr. Rod Eggert and CMI Director Dr. Alex King present the exhibit to CSM Geology Museum Director Dr. Bruce Geller and CSM President Dr. Paul Johnson during the exhibit grand opening reception.

Keeping it Current

The exhibit has already drawn much interest and excitement. Donations and loans of various items for display continue to come in; thus, the exhibit continues to evolve. Additional items (Appendix A and B) include tellurium bars, tablets, and powders. Five rare earth sulfate and acetate crystals were also loaned to the exhibit.

Part of the Exhibit "Goes Green": A unique solar panel installation began from the donation of a CdTe solar panel (from First Solar) and a CIGS panel (from EPRI; made by Solar Frontier) in late 2015-early 2016. These two panels (CdTe and CIGS) are now installed (Fig. 2) and powering a portion of the exhibit, making this the first operating solar photovoltaic module system at CSM. Visitors see the panels as they enter the museum. The installation was enabled by a partnership between Colorado School of Mines and Red Rocks Community College (RRCC), which is made possible through hours of volunteered time and expertise of a solar

contractor and RRCC faculty member, as well as time from an electrical engineer, also a RRCC faculty member. The total dollar value of the installation is an estimated $11,880. Approximately 20 percent of the costs in materials, time, and expertise were donated or volunteered for the installation, including the two solar panels. The costs of the installation were mainly in materials, such as inverters, batteries, and wiring. The overall labor and licensing costs were reduced, mainly due to approximately 48 hours of professional time volunteered by the installers and acquisition of a free professional engineer stamp of approval (typically $350).

Highlighting two different industrial panels for this display has many advantages. The CdTe panel is an efficient and economical alternative to the widely known silicon panels, and it contains the near-critical material tellurium. Including a CIGS panel in the display shows an alternative product that is also efficient and nearly as economic. According to CSM professor, Dr. Joe Beach, "For me, the exciting aspect of CdTe and CIGS is that their laboratory cell efficiencies have both surpassed multicrystalline Si. In the case of CdTe, their commercial panel performance is also higher than multicrystalline silicon, particularly when you take into account temperature-related power loss and spectral sensitivity. If any technology is going to get to $1/W installed system cost profitably, it is very likely to be CdTe (First Solar, in particular). If CIGS producers can achieve the same cost structure that First Solar has with CdTe, then they have a shot also."

The solar display is intended as an educational tool with an interactive component. With the panels at an easy viewing level and distance, visitors gain visual access to panels which are not always accessible to the public. Signs are being designed to provide information about critical materials for solar energy (Te), alternative materials, and other pertinent solar technology. The portion of the exhibit powered by the solar panels will involve an interactive lighting display in which the energy usage of different types of light bulbs (incandescent, CFL, LED, and halogen) will be displayed on a meter when each light is turned on. This interactive display is in the design process. Additionally, an educational event is being planned for September 2016. This event will include a combined lecture and demonstration tour, during which the solar installers will take engineering and STEM students through the installation process. This event will continue to build the relationship between the local Red Rocks Community College and Colorado School of Mines.

Figure 2. Critical Materials exhibit solar display at CSM Geology Museum, with a CdTe panel in the foreground and a CIGS panel in the background. These panels power a portion of the Critical Materials exhibit inside the museum.

With new additions to the exhibit since the Grand Opening, the response from museum visitors continues to be overwhelmingly positive. The presence of the exhibit in the Geology Museum has spurred much conversation with museum guests regarding critical materials. Students of all ages and backgrounds can appreciate the many aspects of critical materials in their daily lives, making the university setting a perfect location for such an exhibit (Fig. 3). The story surrounding critical materials and advanced technologies continues to unfold with every visit.

"The exhibit effectively relates how unfamiliar materials are extracted and processed to manufacture familiar clean energy technology. Guests will leave with an appreciation of material supply chains and their importance for cleanly and sustainably meeting humanity's electricity needs." - Brett Jordan, PhD candidate, Mineral and Energy Economics, CSM

"It's been an eye-opener to the visitors….In our museum, we get a number of repeat guests. It's roughly twenty percent according to our statistics. For the twenty percent who come back all the time, they want to see something new and exciting. The CMI exhibit really fits the bill. It's just perfect for that reason. The fact that it's going to change and evolve over time, that's even more powerful for me as the director here; and, so having the first [critical materials exhibit] in the country, that speaks volumes. This is really, really, cool!" – Dr. Bruce Geller, CSM Geology Museum director

Figure 3. CSM President Dr. Paul Johnson (far left), observes and discusses the exhibit with exhibit designer Mandi Hutchinson (second from left) and CSM KIEM researchers Alyaa Elramady (center), Mark Straus (second from right), and Sumedh Gostu (right) during campus-wide opening reception.

THE CREATION OF A CRITICAL MATERIALS EXHIBIT: IN REVIEW

Partnerships, Donations and Exhibit Loans Make the Exhibit Come Alive

The exhibit was able to come to life only from the many contributors who have given items for display along with their time and expertise. An estimated 88% percent of items on display were donated, loaned or already in the museum's collection (Appendix B). Over 120 hours of expertise were given from volunteers and partners (Appendix A). All donors and volunteers were recognized at the "soft" and "grand" opening receptions, and all donated items on display show acknowledgement of the gift or loan from the donor (Appendix B). The estimated total cost of the exhibit is valued at $87,313; of which $29,508 of donated goods, donated time and expertise, and discounts are included. This does not include the time and/or salaries of the three exhibit developers. Both totals are conservative amounts, given that the values of 31 out of 71 donated and loaned items plus some specimens from the museum's collection are unquantifiable; these are priceless, one-of-a-king materials, and include such items as ore samples (Fig. 4), research samples (Fig. 5a, b), metallurgical samples (Fig. 4), demo phones (Fig.6), and dead batteries (Fig. 6). In many instances, these items can only be attained from strategic partnerships.

Figure 4. Ore samples from the Mountain Pass, CA rare earth mine (donated by USGS, Brad Van Gosen) and ore samples and metallurgical testing samples from the Bear Lodge, WY rare earth deposit (donated by Rare Element Resources).

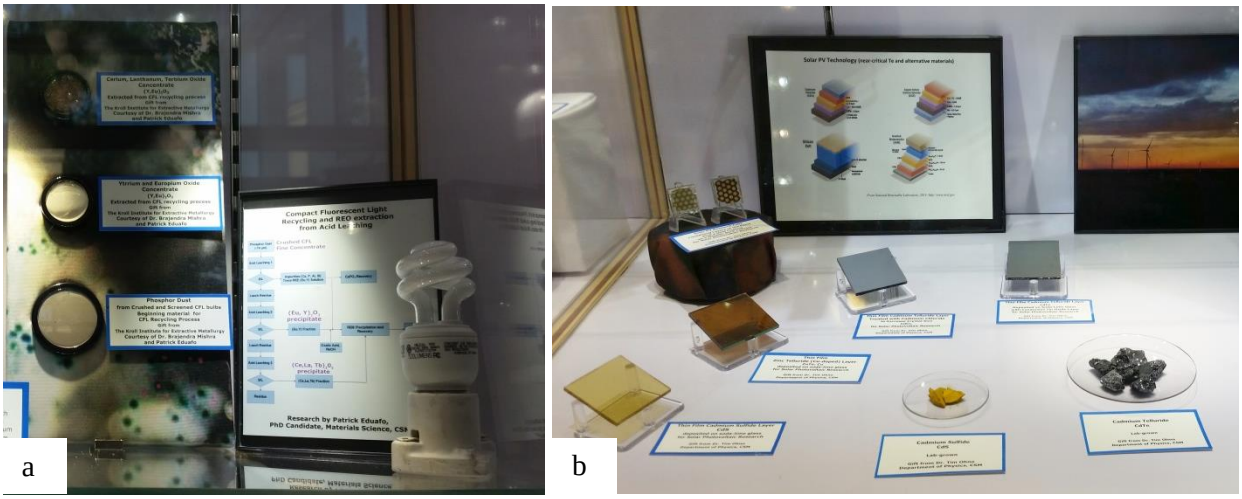

Figure 5. (a) Rare earth recycling and extraction research materials from PhD researcher, Patrick Eduafo, with the Kroll Institute for Extractive Metallurgy (KIEM), CSM. (b) Photovoltaic research materials and samples from CSM professor Tim Ohno and his students.

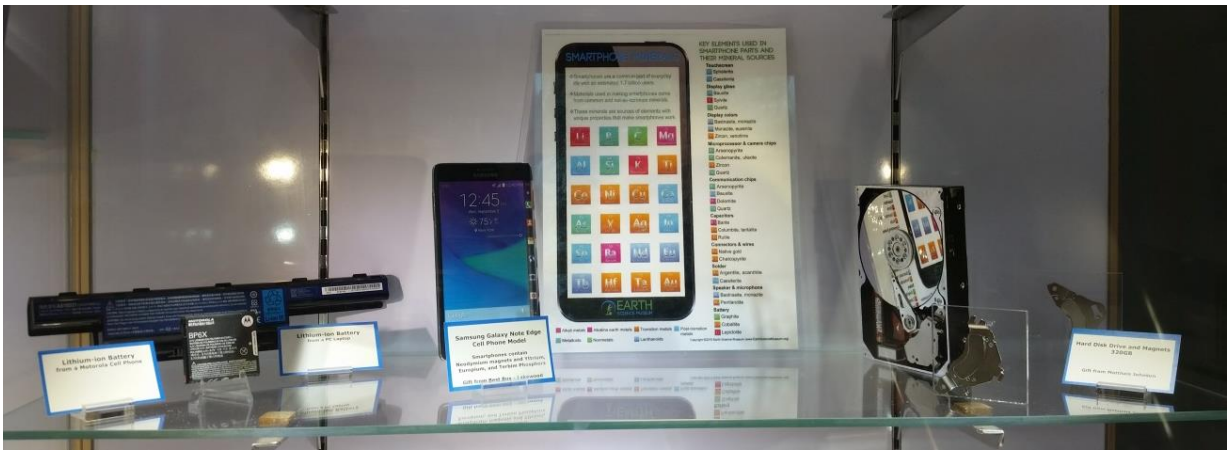

Figure 6. Advanced technology and energy storage items, all were donated for the exhibit.

Meeting the Original Goals

Throughout the development of the exhibit, the team continued to follow the goals developed by the team and listed in the first "How-to" report. These goals were the cornerstone for any brainstorming and decision-making regarding the design, organization, and structure for the museum display. The following is a list of six original goals and how those goals were met.

- **Ensure the display represents the Critical Materials Institute goals and outreach ideals**

- Informing the public of CMI's mission in diversifying supply (CMI research thrust) was accomplished with the inclusion of phosphate processing samples as an alternative resource.
- Developing substitutes (CMI research thrust) was highlighted with the inclusion of LED bulbs as a replacement for CFL bulbs. LED bulbs use fewer rare earth elements and less energy than the formerly cutting edge CFL bulbs (Fig. 6).
- Improving reuse and recycling (CMI research thrust) was shown with the products from CSM research in recycling CFL bulbs, which exhibits the extraction of critical materials from the light bulbs (Fig. 4,a). Additionally, the recycling focus is shown in the video display covering the Ames Laboratory research on recycling magnets from the factory floor.
- Crosscutting research (CMI research thrust) is touched upon in the video showing the advanced metallurgical process developed by RER that focuses on sustainability and environmental consideration.
- Regarding outreach, the exhibit is highly accessible to the nearly 40,000 museum attendees spanning all ages, ethnicities and educational backgrounds.

Figure 6. The importance of critical materials in energy efficient lighting (CFL's and LEDS) demonstrated in the "product" case. The role of developing substitutes, like LED bulbs which are more energy efficient than CFL's and use fewer rare earth elements, is one of CMI's research thrusts.

- **Ensure the display fits into the design and goals of the CSM Geology Museum**
  - In keeping with the overall aesthetics in the museum, a maple veneer case exterior, and white interior was selected for the display cases (Fig. 7).
  - Some black was used in additional displays, which also fits into the colors already used in the surrounding areas of the museum.
  - Contain components that garner interest from all ages of visitors.

Figure 7. The Critical Materials museum exhibit, showing the video display alongside the source, process, and product display cases. The cases were designed with a maple exterior and a white interior in keeping with the overall aesthetics of the museum cases. A maple finish was also incorporated into the video display design.

- **Lower costs by utilizing what is already available in the museum, including display cases, display space, materials (minerals, processed materials, etc.)**
  - The minerals on display were the main portion of the exhibit and were loaned from the museum resources. Approximately three fifths of the minerals on display were sourced from the museum's massive archived collection.
- **Consider the multiple parts of the exhibit, that each part can be separated, stand alone, rearranged and/or built upon to ensure a lasting sustainable exhibit**
  - The exhibit cases, video display, and components of the exhibit were designed in three sections that could easily stand alone, be added to or taken from and/or be moved into other exhibit spaces as the museum changes to meet new standards, address audiences, reflect changes in society and/or research.

  - The items purchased and donated for the exhibit are now part of the museum's collection. Aside from loaned items, everything in the exhibit will remain with the museum and under the care of museum personnel.

- **Remember to make the display versatile and malleable so that it can remain current, including how to fund new additions and consider the museum's goal of changing 25% of the displays each year**
  - Since the museum's collection consists mainly of donated items/specimens, additional items can be acquired through a donation-only process. The Friends of the CSM Geology Museum occasionally purchase new mineral specimens for the museum but this is rare and could be a potential option going forward based on museum priorities.
  - It has become apparent that the exhibit could easily expand to occupy additional space, due to the overwhelming amount of donated items we have received for this project. With the planned additions to the exhibit (items and solar installation), the exhibit will reach a maximum capacity. If new donations are received, a portion of the display may need to be removed to accommodate new items. Already, we are seeing a potential for the museum's annual display changes including part of the critical materials exhibit, complementing the museum's 25% change-out goal.
- **Engage young minds by representing inspiring science and engineering and causing them to question, dream, and envision themselves solving problems and inventing new technologies. Focus on the aesthetics of each component and demonstrate how the critical materials affect daily lives.**
  - Younger visitors to the museum are immediately engaged and immediately drawn in by the brightly lit cases, the color, the interactive displays (video display and phosphor light box), and the very tangible and accessible items in the exhibit (wind turbine that you can touch and view inside, an industrial solar panel to inspect, cell phone and computer parts, and a spinning magnet "orb").
  - The accompanying and colorful and informative banners explain the story of Critical Materials more directly, and young visitors have even become engaged in discussion regarding supply chain disruption while sitting on a bench nearby and pondering a tour guide's address.
  - Students are able to directly see and connect the dots from ore samples to materials to advanced technologies of their day and imagine what their world would be like without these materials. As they ask questions and are asked questions, the story of the importance of these materials unfolds.
  - Since the exhibit is adjacent to the "classroom" area of the museum, where the rock cycle is commonly discussed with student tours, discussions can easily occur, bridging critical materials and ore deposits. Some high school tours have delved into discussions about the environmental aspects of various ore deposits of the critical

materials while exploring the logistics of each. You can actually almost see their brains churning.

- Most importantly, student groups can begin to make connections and applications to their classroom content and knowledge of geology, technology, energy resources, and environmental issues, etc. After all, this is a research to classroom exhibit, and we expect teachers and students to connect this experience back into the classroom and their daily lives.
- In the end, we hope that children begin dreaming of becoming scientists, technicians, engineers, and mathematicians who will impact the world's future advanced technologies and discoveries. We hope they consider these fields as an option for their future contribution to mankind and as careers.

Challenges and Advantages

Challenges

The challenges discussed in the first report remained largely the same throughout the project development. These challenges and their outcomes are noted below.

- **Sourcing museum quality minerals of larger size (larger than thumbnail) are not widely available.**
  - Securing such minerals eventually became less of a problem due to the museum's reputation and resources. The museum collections manager, Ed Raines, was able to locate several mineral specimens from Collector's Edge Inc. which were not readily available to the public.
  - It took some time for the desired quality of minerals to become available on the market; however, with time, all of the desired minerals were acquired by purchase or loan.
  - One of the main challenges with sourcing museum quality minerals became working through procurement questions for such out of the ordinary purchases. As our procurement team became more aware of the need, they responded by developing a new purchase code just for our exhibit and accepting and readily moving procurements through the system.
- **Sourcing REE-oxides/phosphors and finding an aesthetic way to display them.**
  - Sourcing and displaying became easier when our team reached out to CSM researchers and laboratories for assistance with ordering chemicals. The chemicals on display in the exhibit were either donated by or purchased through multiple CSM laboratories.
  - CMI researcher and Iowa State faculty, Dr. Vitalij Pecharsky, made recommendations and shared display items with us; we then partially emulated the way rare earth oxides are on display at Ames Laboratory (Figures 8a, b).
  - Showing phosphorescence in a museum exhibit can be challenging. Fortunately, the museum had one of two available fluorescent viewing boxes from the museum

collection. The box is a type of exploration lab/field equipment for viewing petroleum inclusions under white and longwave UV light. The lab/field equipment box was a perfect way to show off the phosphorescent/luminescent qualities of the phosphors (Fig. 9) used in CFL bulbs. This system also added an interactive component to the exhibit.

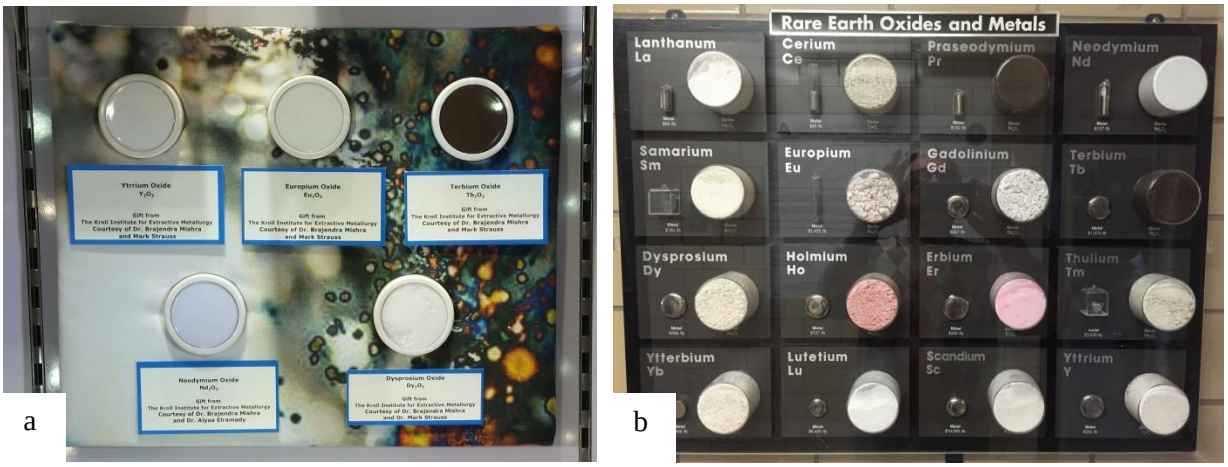

Figure 8. (a) Rare earth oxide powders on display in the CSM Geology Museum Critical Materials Exhibit. (b) Rare earth oxide powders on display at Ames Laboratory, courtesy of Dr. Vitalij Pecharsky.

Figure 9. The view when looking into the phosphor viewing box. This photo shows the rare earth-doped phosphors illuminated with longwave UV light. Note that the obstruction on the bottom left of the image is from a built-in magnifying lens and is not present when actually viewing in-person.

- **Sourcing crystallized REE-metals with crystal form was difficult, because they are not widely available.**
  - We eventually relinquished the idea of displaying the REE metals with crystal form as we found only one source for all of the rare earth metals. The metals would have been mainly cut metal pieces without crystalline form; required a sealed ampule casing or safety and metal integrity. We quickly realized there was little value in a display with metals that all look the same and are difficult to view in the ampule casing.
- **Additional Challenge: The video display became a very challenging aspect of the exhibit.**
  - The video display was configured with an electronic tablet device and an external monitor and speaker, requiring more person hours and expertise than anticipated. The purpose of using a tablet was accessibly for updates, new videos, etc. to the museum staff, while retaining touch technology ease of use for visitors. This all seemed simple; but in hindsight, we agreed that we should have hired a professional to install and configure this portion of the display.
  - Giving an undergraduate engineering student the opportunity to create a program for the display did prove to be a positive educational experience. However, working within a Windows operating system created several hurdles to overcome. A lot of time and effort was expended programing and understanding the operating system functions. Building a secure housing device for the tablet also took a lot of time and resources. We recommend building and assembling display components at the beginning of your installation to ensure operability at the time you expect it and in the future.
  - The video display stand (minus the computer and video technology components) was designed by our team and built by a professional (Appendix B). The aesthetics and functionality of the stand work well within the exhibit (Fig. 7).

Advantages

The advantages recognized in the first report remained the same throughout the project development, with the exception of the final point made at the end of this list.

- Association with CMI allowed access to some display components through CMI labs, university resources, and industry partners (a vast energy hub of over 300 researchers spread across the nation in over six universities, four national labs and multiple industry partners).
- An academic atmosphere provides a unique opportunity to engage previous, current, and future students and perhaps the future workforce. Much expertise and many items for display were sourced from the unique atmosphere of the CSM campus which hosts over 35 research centers and institutes.

- Location of the display in the CSM Geology Museum offered security, visibility, and museum-quality resources and expertise at our finger tips. With nearly 40,000 national and international visitors annually, spanning all ages and backgrounds, the museum's special atmosphere proves to be a valuable and logical selection for the location of this exhibit.
- The association with CMI and with CSM's geology museum has attracted many donors to the exhibit. Donors recognize the value of such a display and want to be a part of this exhibit through their contributions. Donors are still coming forward to contribute. Even at this date of writing, when the exhibit is considered complete, we are placing additional donated items that add something new to the exhibit (exhibit sustainability and change over goals discussed above).

Feedback and Evaluation Providing New Ideas and Validation

In order to ensure that the exhibit continues to meet the goals (outlined above), our team has solicited feedback through evaluation surveys. Evaluation cards were available to fill out at both the campus-wide exhibit opening and the grand opening exhibit dedication ceremony. We continue to solicit evaluations from CSM students and researchers and through any educational groups attending the exhibit. This evaluation is available online for visitors to give feedback at https://cmi.ameslab.gov/content/critical-materials-museum-exhibit-evaluation. Additionally, the evaluation is accessible when viewing the exhibit for those able to scan the QR code on display. The feedback received from evaluations completed at the opening receptions was very positive overall and has provided new ideas for ways to improve the exhibit. This positive feedback has validated the importance of the exhibit and has demonstrated the exhibit team's success. Evaluation comments below describe visitor perspectives and experiences.

- *"Beautiful examples of source minerals for [critical materials]."* – Anonymous grand opening attendee

- *"The display of which minerals contain critical materials was great – I didn't realize that many common minerals had that use. I liked the oxide powders too."* - Anonymous grand opening attendee

- *"Beautiful specimens! Good tie between 'Geology Museum' and 'what we use these minerals for and why we need them.'"* - Anonymous grand opening attendee

- *"I like it all. Very educational, informative and exciting for all ages."* - Anonymous grand opening attendee

- *"Thanks for having a display on this important topic."* - Anonymous grand opening attendee

For additional information regarding specific exhibit components, accompanying educational materials, and how to design such an exhibit for your area, contact CSM Geology Museum Director Dr. Bruce Geller at bgeller@mines.edu or CMI Education, Training and Outreach Manager Dr. Cynthia Howell at chowell@mines.edu. You can also access these resources at the CMI website: cmi.ameslab.gov.