

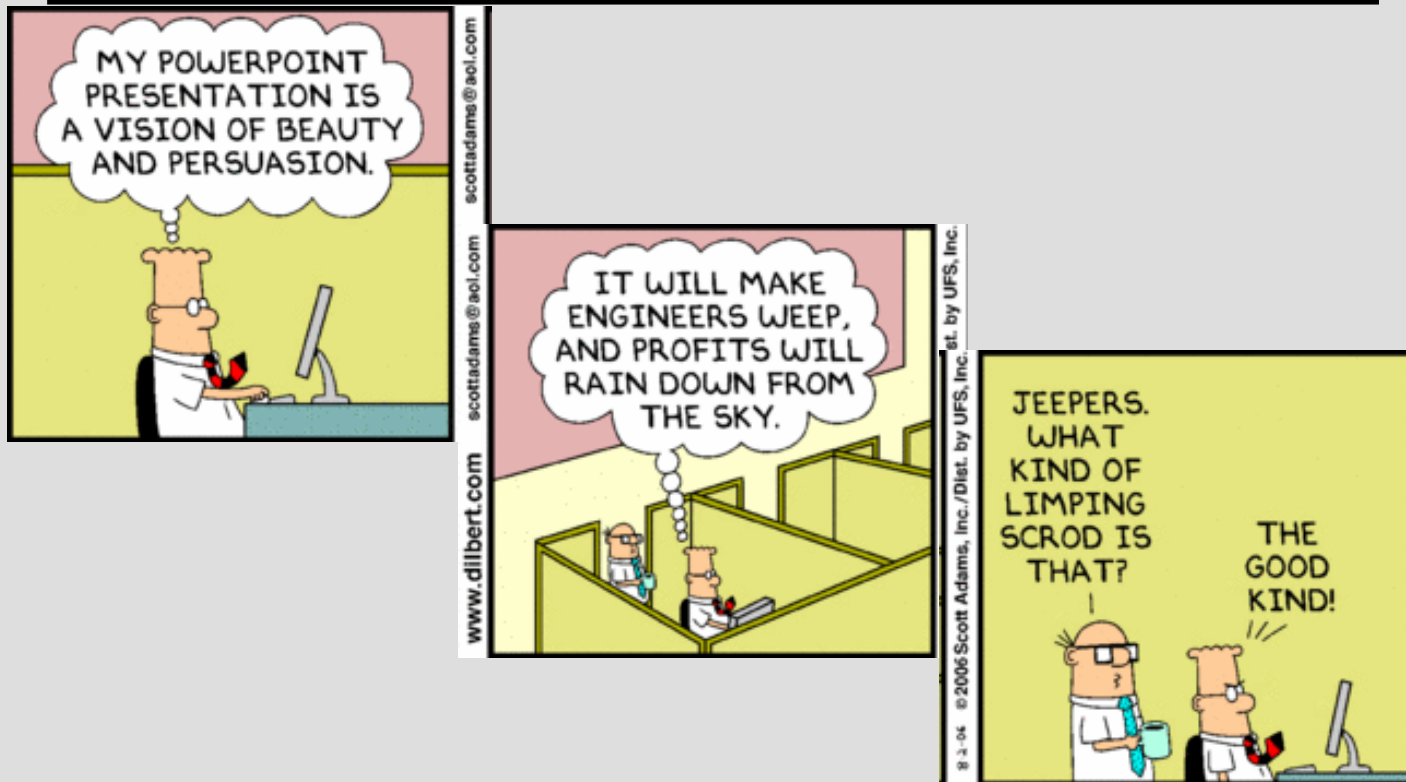
The Kroll Institute for Extractive Metallurgy

45 Years of Success in Research and Education

Dr. Corby G. Anderson
Harrison Western Professor

Kroll Institute for Extractive Metallurgy
Colorado School of Mines

PROFESSIONAL PRESENTATION PHILOSOPHY



**ANDERSON ANCESTORS 1891
FROM LINDBERGE PARISH, HALLAND, SWEDEN
BUILT & OPERATED THE ANACONDA SMELTER**



The Stack was built by the Alphons Custodis Chimney Construction Company of New York. At the time it was built, May 5, 1919 it was the tallest masonry structure of any kind in the world at 585 feet.

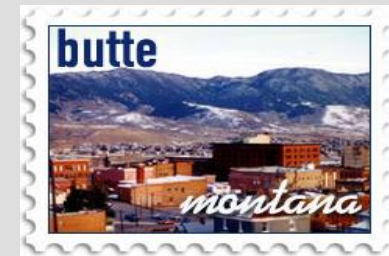
“Nothing is good enough if it could be made better and better is never good enough if it can be made best.”

HARRINGTON CORBY ANCESTORS 1873 COPPER MINERS FROM ALLIHIES PARISH, BEARA PENINSULA, COUNTY CORK, IRELAND



*“Irish people are educated not only about artistry
but local history.” – Fiona Shaw*

MY HOMETOWN - BUTTE AMERICA



“A Mile High and a Mile Deep but the People are on the Level”

Colorado School of Mines

- Est. 1874
- Golden, Colorado
- 3 Colleges & 21 Technical Majors
- About 200 Faculty
- About 6000 Students
- “...has a unique mission in energy, mineral, and materials science and engineering...”
- “has the best balance between teaching and research of any public university.”
- “QS ranked #1 in the World for Mining and Mineral Engineering” by Business Insider.
- “Ranked as #1 US Engineering school” by USA Today.
- “Mines has the brainiest students of any public university.” Luminosity survey.
- Recently named as the #1 US Engineering school by College Factual.
- “the average starting salary of a BSc Mines graduate is \$ 10 K more than an Ivy League graduate.”



The Kroll Institute for Extractive Metallurgy

Tomra Optical Sorting Seminar at Colorado School of Mines

October 22, 2019

Challenges to the mining industry only continue to grow. Sensor-based sorting proves to be an increasingly more important tool, both to formulate optimal solutions for greenfields projects and to help conquer challenges for keeping brownfields operations viable.

This seminar is the first of its kind, encompassing a broad range of topics including sorting technology, applications, plant design, economic considerations and more.



The Kroll Institute for Extractive Metallurgy

Recycling Metals From Industrial Waste

29th Annual Short Course

June 23-25, 2020

Professors Queneau and Spiller

Recycling Metals from Industrial Waste, now in its 29th year, focuses on current plant practices to convert metal-containing wastes to products. Processors, raw materials, and markets are identified and quantified. Speakers with decades of hands-on experience detail multiple approaches to recycling metals and associated materials - backed up by slides, videos, and the syllabus.



The Kroll Institute for Extractive Metallurgy

New Directions in Mineral Processing Fundamentals

35th Annual Short Course

July 2020

Professors Taylor, Anderson, Spiller and O'Kelley

The course emphasizes the unit operations used in industry and their application to operations as follows:

- *Feed characterization (mineralogy, size, liberation)*
- *Comminution (size reduction via crushing, grinding, and etc.) for liberation*
- *Particulate separation based on particle size, floatability, specific gravity, magnetic susceptibility, conductivity, and other mineral traits*
- *Liquid-solid separation*
- *Process flowsheets and their control*
- *How to know how well your plant is operating*



The Kroll Institute for Extractive Metallurgy



Patrick R. Taylor, Director KIEM
Department of Mining
Engineering, Colorado School of
Mines



Expertise for the Mining and Minerals Industry



- ✓ **Colorado School of Mines is one of the few US institutions that has the necessary integration to provide education and research across the full technical spectrum required by the mining, minerals and metals industries.**
- ✓ **The School has a long history of support from, and for, the minerals industries.**
- ✓ **We would like to continue to serve this industry and to grow our capabilities.**

The Kroll Institute for Extractive Metallurgy



Dr. William Justin Kroll was a Luxembourg metallurgist.

He is best known for inventing the Kroll process in 1940 in conjunction with the USBM which is used commercially to extract metallic titanium and zirconium from ores.

This created an entirely new material and industry !

Born: November 24, 1889, Luxembourg

Died: March 30, 1973, Brussels, Belgium

“good metallurgists are not born. They are made with the ample money of the companies which hire them, and since they usually make their mistakes on a grand scale, they are the nightmares of business management.”

1943 Perkin Award Speech Quotation by Dr. William Kroll

“KIEM - Excellence in Education and Research for the Mining, Minerals and Metals Industries”

- **History: *The Kroll Institute for Extractive Metallurgy was established at the Colorado School of Mines in 1974 using a bequest from William J. Kroll.***
- ***Over the past 42 years, the Kroll Institute has provided support for a significant number of undergraduate and graduate students who have gone on to make important contributions to the mining, minerals and metals industries.***



- **Objectives: *The objectives of KIEM are to provide research expertise, well-trained engineers to industry, and research and educational opportunities to students, in the areas of : minerals processing, extractive metallurgy, recycling, and waste minimization.***

KIEM Kroll Institute for Extractive Metallurgy



Patrick R. Taylor
Director, KIEM
Associate Director, CR3
George S. Ansell Distinguished
Professor of Chemical Metallurgy

- Mineral Processing
- Extractive Metallurgy
- Recycling
- Waste Treatment & Minimization
- Thermal Plasma Processing



Corby G. Anderson
Associate Director, KIEM
Director, CR3
Harrison Western Professor of
Metallurgical and Materials
Engineering

- Extractive Metallurgy
- Process Metallurgy
- Mineral Processing
- Recycling
- Waste Treatment & Minimization



Gerard P. Martins
Professor Emeritus of
Metallurgical and Materials
Engineering

- Process Metallurgy
- Extraction Metallurgy
- Electrochemical systems
- Electrometallurgy
- Corrosion
- Materials Synthesis



Brock O'Kelley
Research Associate Professor of
Metallurgical and Materials
Engineering

- Extractive Metallurgy
- Process Metallurgy
- Waste Minimization
- Plant Design, Start-up and Operation
- Optimization



Paul Queneau
Research Professor of
Metallurgical and Materials
Engineering

- Extractive Metallurgy
- Recycling of Lead, Zinc, Cadmium, Tin, Copper, Nickel, Cobalt...
- Resource Location
- Byproduct Marketing



Sridhar Seetharaman
Professor of Metallurgical and
Materials Engineering

- Extractive Metallurgy
- Iron and Steelmaking
- Refining, Casting and Oxidation
- Low Carbon Materials Technologies



D. Erik Spiller
Research Professor of
Metallurgical and Materials
Engineering

- Mineral Processing
- Comminution/Liberation
- Particulate Separation
- Feasibility Studies
- Operations and Project Management



Edgar E. Vidal
Research Associate Professor of
Metallurgical and Materials
Engineering

- Extractive Metallurgy
- Process Metallurgy
- Materials Synthesis
- Pyrometallurgy
- Electro Metallurgy
- Business Development



Judith C. Vidal
Research Assistant Professor of
Metallurgical and Materials
Engineering

- Extractive Metallurgy
- Process Metallurgy
- Materials Synthesis
- Recycling
- Electrochemical Systems

The Kroll Institute for Extractive Metallurgy

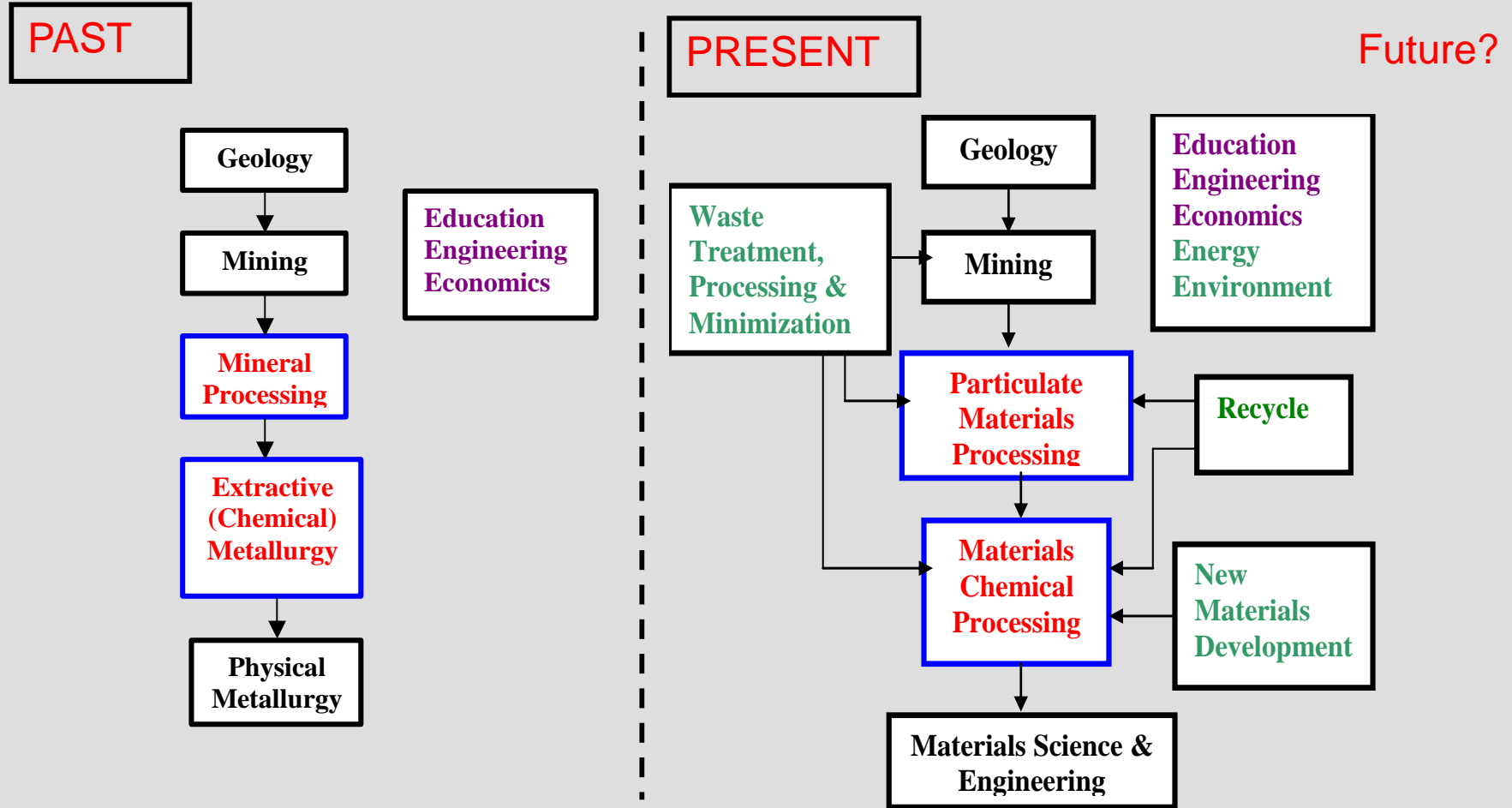
kiem.mines.edu



Mineral Processing/Extractive Metallurgy

- Mineral Processing – the utilization of methods to separate valuable minerals (or metals) from waste minerals (or recycled materials)
- Hydrometallurgy – the utilization of aqueous environments to remove metals from minerals (or recycled materials), to separate dissolved metals from each other, to recover metals from solution.
- Pyrometallurgy – the utilization of elevated temperatures to modify the chemistry of minerals, to reduce minerals to metals, to refine metals, etc.
- Electrometallurgy – the utilization of electricity to recover and to refine metals, etc.

Mining, Mineral Processing & Extractive Metallurgy – Past & Present



How our accomplishments are transferred to supporters

As most of our projects are applied and done with industry involvement, accomplishments are transferred through:

- **Utility of the results**
- **Patents**
- **Technical publications**
- **Graduate MS and PhD Theses**
- **Trained Engineers**

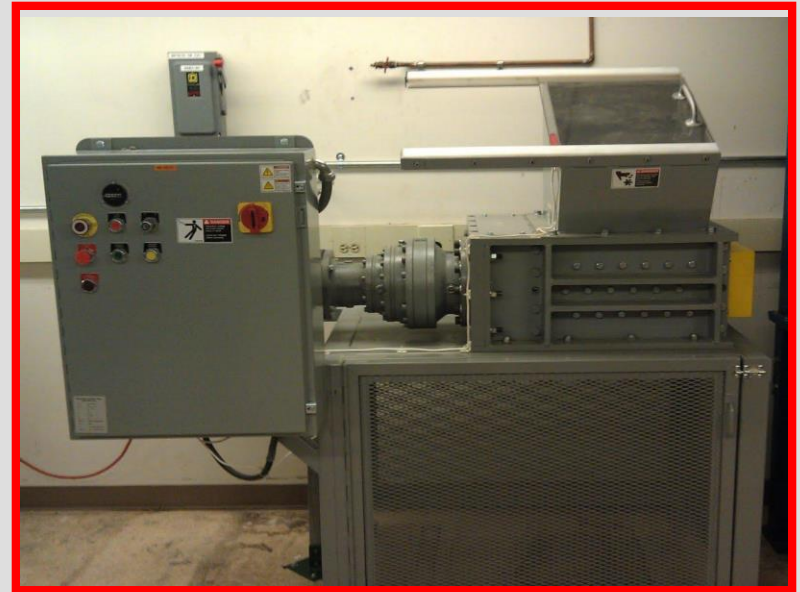
Facilities: Chemical Analysis

- AAS
- ICP-MS
- UV/VIS spectrophotometer
- XRF
- LIBS
- SEM with EDS TEM
- X-Ray diffraction
- QEMSCAN (in Geological Engineering)
- Spark OES
- Fire Assay



KIEM Facilities: Mineral Processing

- Crushing (laboratory scale jaw, rolls and cone crushers)
- Shredding (plastics and used electronics shredder)
- Grinding (Spex mill, pulverizers, ball and rod mills, Bond ball work index mill, 1 m by 0.5 m instrumented batch mill)
- Screening (Ro-tap and Gilson screens and systems)
- Hydrocyclone test unit



KIEM Facilities: Mineral Processing

- Magnetic separators (various low and high intensity magnetic separators; both wet and dry, rare earth roll and drum)
- Electrostatic separator
- Eddy current separator
- Gravity separators (Super panner, Wilfley table, Knelson concentrator, and jig)
- Flotation (Zeta Meter, tensiometer, Micro-flotation cell, laboratory scale Denver cell and column flotation systems)
- Dense media test system (low-viscosity polytungstate)



Facilities:

Hydro- and Electrometallurgy

- Solvent extraction
- Leaching systems (agitation and pressure)
- Ion exchange
- Precipitation
- Electro-winning (aqueous and molten salt)
- Electro-refining
- Constant temperature baths (with and with out agitation)
- On-line aqueous ion and property measurement with data acquisition (Eh, pH, dissolved oxygen, specific ion electrodes)



Facilities: Pyrometallurgy

- High temperature furnaces (tube, crucible, lab scale rotary kiln, pilot scale rotary kiln)
- Viscosity measurement system
- Density measurement system
- Partitioning measurement system
- Press and sintering system
- DSC/DTA system
- On line gas analysis (IR) and gas chromatography
- Plasma reactors (RF, Plasma spray, DC transferred and non-transferred arc systems)
- On-line data acquisition systems



University Partners

CR³ Center for Resource
Recovery and Recycling



WPI

Worcester Polytechnic Institute



Colorado School of Mines



KU Leuven



University of Tokyo

Our Team

CR³ Center for Resource
Recovery and Recycling



Brajendra Mishra



Diran Apelian



**Corby G.
Anderson**



Bart Blanpain



Toyohisa Fujita

Our Recent Members

CR³ Center for Resource
Recovery and Recycling

- ICL
- Aurubis
- East Penn Manufacturing
- General Motors
- Global Mineral Recovery
- Gopher Resource
- Heritage Environmental
- Hydro Aluminum Rolled Products
- Indium Corporation
- JX Nippon Mining & Metals
 - Metallo Belgium
 - nanoRanch
 - Olympus
 - SMS Group
 - Boliden
 - Surface Combustion
 - Tianqi Lithium
 - Umicore
 - U.S. Army Research Laboratory

Our Members

CR³ Center for Resource
Recovery and Recycling



CR3 Meeting, The University of Tokyo, Tokyo, Japan May 23-24, 2017



Critical Materials Institute

AN ENERGY INNOVATION HUB



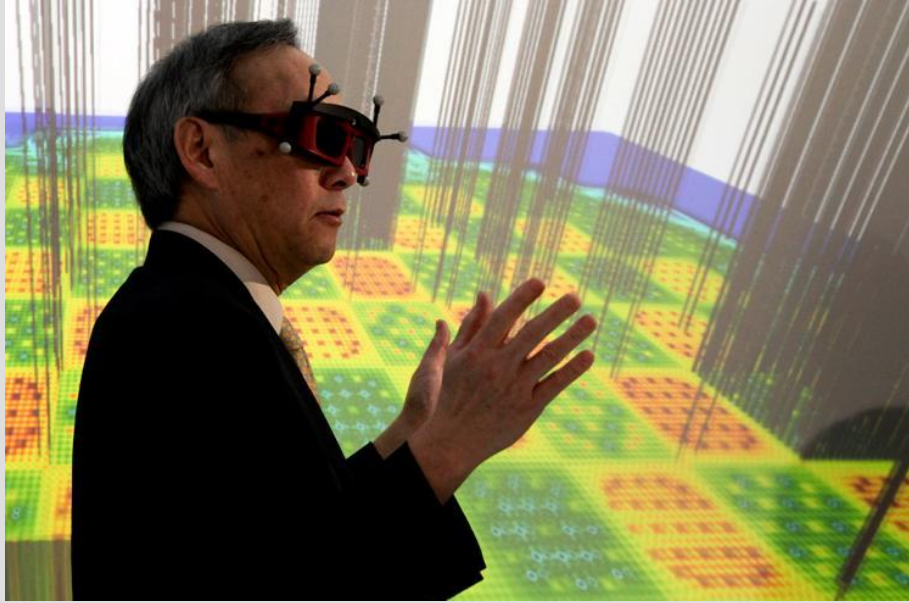
RioTinto



The Kroll Institute for Extractive Metallurgy



What are Energy Innovation Hubs?



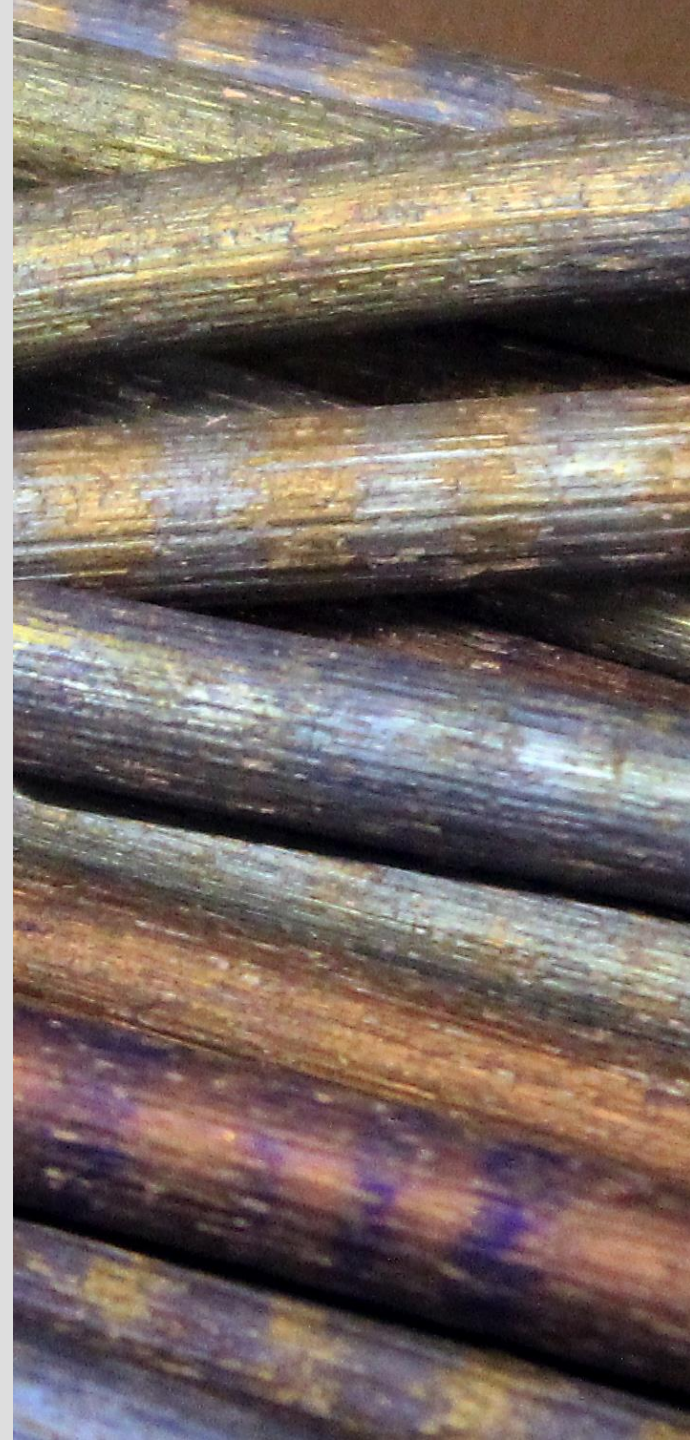
Integrated research centers that combine basic and applied research with engineering to accelerate scientific discovery in critical energy issue areas.

- Leadership is vested in scientists who are given the authority to assign funds where they are most effectively used
- \$20M - \$25M per year, for 5 years, now renewed for an additional five.

- CASL: Consortium for Advanced Simulation of Light-Water Reactors
- EEB: Energy Efficient Buildings Hub
- JCAP: Joint Center for Artificial Photosynthesis
- JCESR: Joint Center for Energy Storage Research
- CMI: Critical Materials Institute

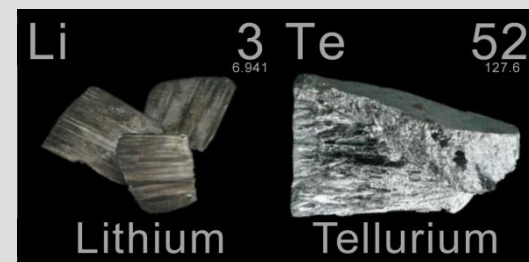
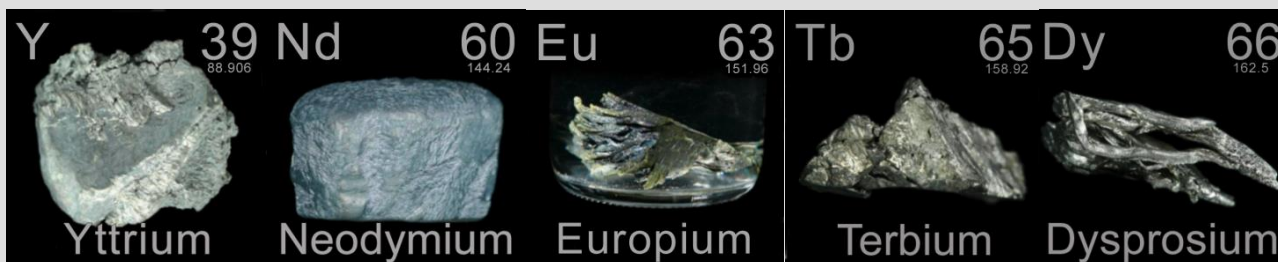
What is a “Critical Material?”

- Any substance used in technology that is subject to supply risks, and for which there are no easy substitutes.
- Or, in plain English – stuff you really need but can’t always get.
- The list of materials that are considered critical depends on who, where and when you ask.
- CMI focuses on clean energy technologies, in the US, over the next 10 to 15 years.



The Mission of CMI

Eliminate materials criticality
as an impediment to the
commercialization
of clean energy technologies
for today and tomorrow.

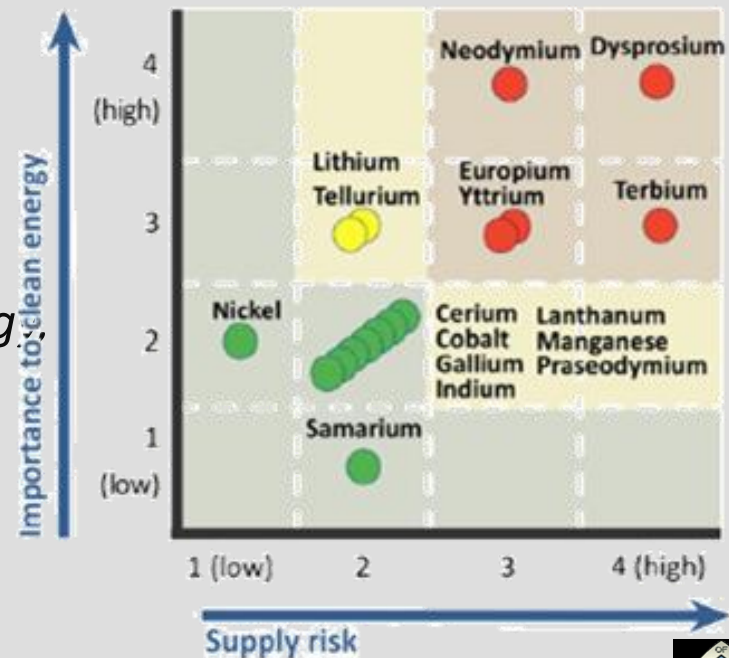
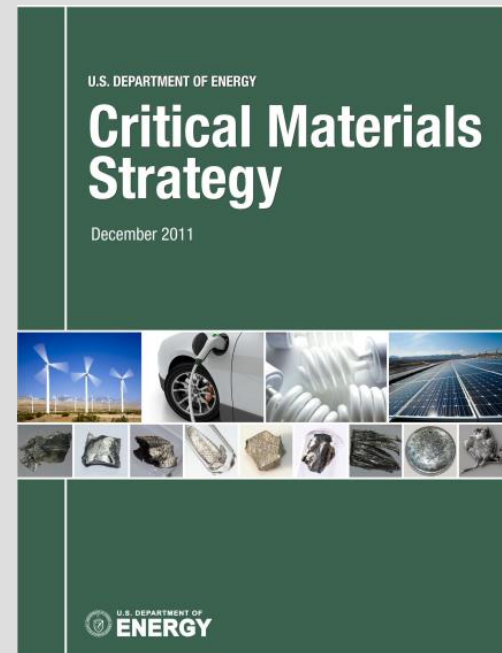


Three-D Approach

- Diversify supply
- Develop substitutes
- Drive reuse, recycling, and efficient use of materials in manufacturing

Essentially following DOE's Critical Materials Strategy but applying it very selectively

Medium Term Outlooks:
2015 – 2025



Two Guiding Principles

- Produce more

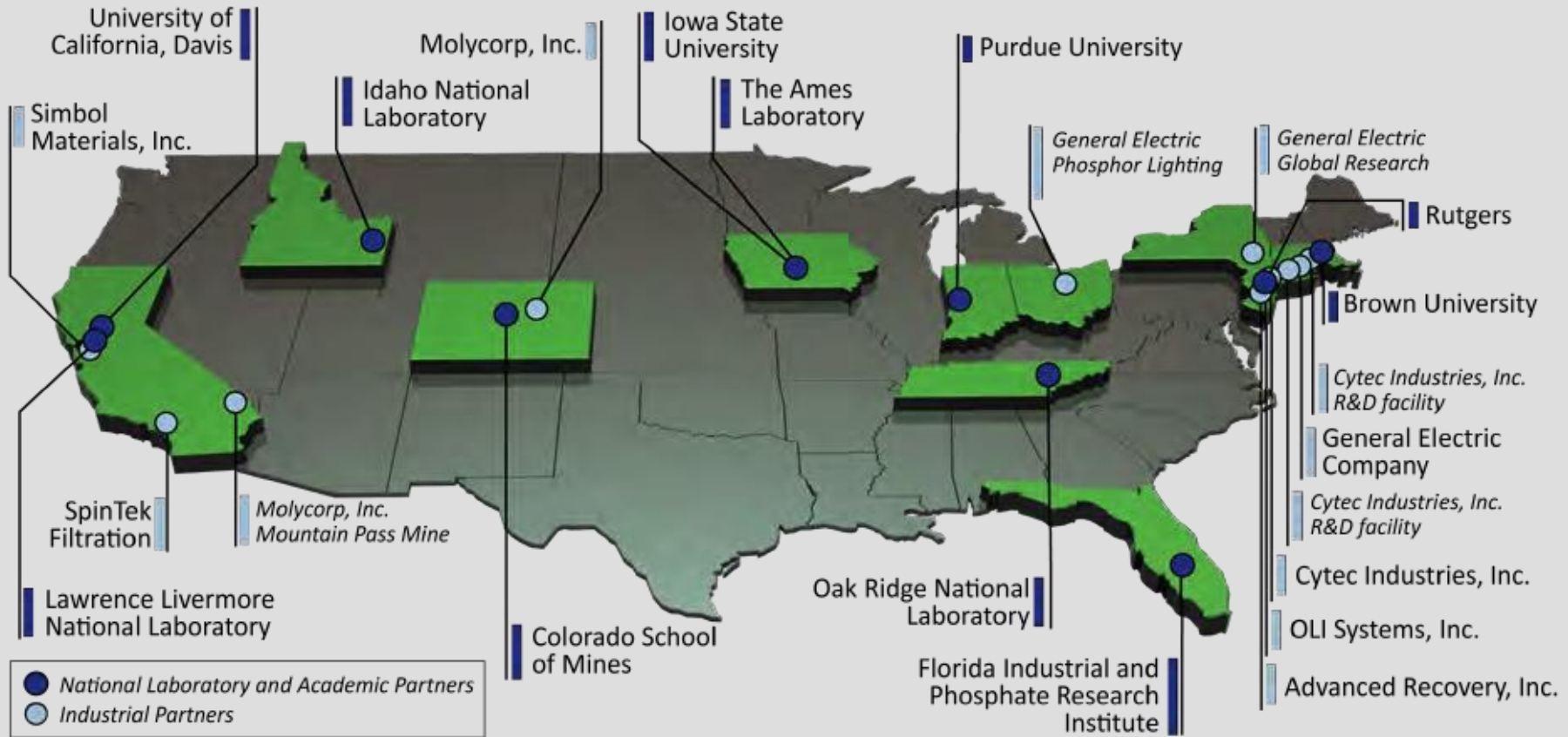


- Use less



- We have to address the entire materials lifecycle, going from birth through death, and beyond, to include resurrection.

One Integrated Team





Current Projects at Colorado School of Mines

- **Advanced Beneficiation Techniques**
- **Conversion to Metals, Alloys and Materials**
- **Cost Effective Recycling of Rare Earth Containing Magnets**
- **Beneficiation of Functional Coatings**
- **By Product Critical Material Recovery**
- **Improved Leaching and Ion Exchange of Rare Earths**
- **Cerium Aluminum Alloy Production**

Example Industry Direct Funded Projects

- ✓ **Controlled Pressure Oxidation of Enargite Concentrates.**
- ✓ **Rare Earth Recovery from Thermal Spray Powder Wastes.**
- ✓ **Fundamental Study of Commercial Gold Roasting Operation.**
- ✓ **Ion Exchange Separation Technologies for Rare Earths.**
- ✓ **Metal Reduction Technologies for Rare Earths.**
- ✓ **Controlled Oxidative Roasting of Enargite Concentrates.**
- ✓ **Iron Precipitation Phase Determination in Copper Concentrate Pressure Oxidation.**
- ✓ **CFD Modeling and Slag Chemistry for Secondary Lead Processing.**

Example Industry Direct Funded Projects

- ✓ DEM for Attrition Scrubbing of Thin Films
- ✓ Bazin Method Determination of Gold Cyanidation Liberation
- ✓ Impurity Removal From Auto Shredder Steel Scrap (REMADE)
- ✓ Minor Impurity Recovery From a Copper Smelter
- ✓ Gold and Cyanide Recovery From Copper Flotation Tailings
- ✓ Primary Lithium Leaching and Separation
- ✓ Determination of Diffusion Coefficients for Gold Heap Leaching

Industry Funded Projects - Current and Recent

Center for Resource Recovery and Recycling – NSF Industry Consortia

- ✓ **CR³ – Beneficiation of Photovoltaic Coatings**
- ✓ **CR³ – Recovery of Rare Earth Metals from Phosphor Dust**
- ✓ **CR³ - Recycling of Bag-house Dust from Foundry Sand**
- ✓ **CR³ – Zinc Removal from Galvanized Scrap**
- ✓ **CR³ – Indium and Rare Earth Recovery from Used Plasma Display Panels**
- ✓ **CR³ – Recycle of Rare Earth Magnets**

Industry Funded Projects - Current and Recent

Center for Resource Recovery and Recycling – NSF Industry Consortia

- ✓ **CR³ – Red Mud Recycling**
- ✓ **CR³ – Recycling of Fines**
- ✓ **CR³ – Hydrometallurgical Treatment of Used Circuit Boards**
- ✓ **CR³ – Vacuum Distillation of Complex Lead Bullion**
- ✓ **CR³ - Ga, Ge and In Recovery From Zinc Plant Residues**
- ✓ **CR³ – Water Borne Paint Sludge Recycle**

SUMMARY THOUGHTS

- There are about 8 US schools left that teach and research Mineral Processing and about 4 that teach and research any Extractive Metallurgy.
- The average age of the faculty engaged in these activities is well over 50 years old.
- An H Index is more important for hiring, tenure and promotion of faculty than any real world practical engineering knowledge that can be passed on to students.
- The US Bureau of Mines no longer exists so there is no single agency that fully represents a relatively globally large GDP sector for the USA.
- Corporate research and development barely exists.
- Over one half or more of the experienced mineral and metallurgical engineers will retire in less than ten years.
- As an analogy, will you now hire a plumber if you need an electrician ?

SUMMARY THOUGHTS

Central South University, Changsa China

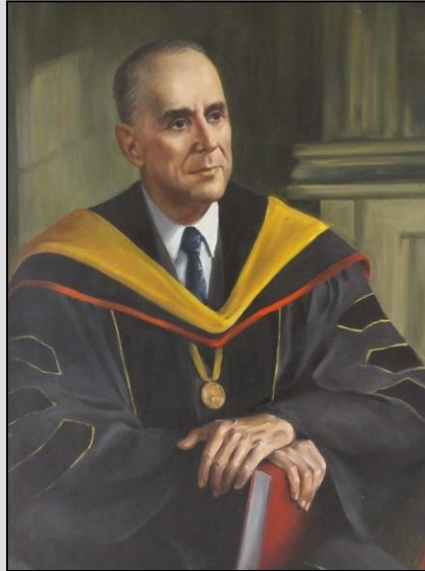


The largest of **38** Mineral Processing schools in China.
1000 Undergraduates and 500 Graduate Students !

Extractive Metallurgy is in a large but separate school !

Professor Spiller and I will visit Central South November 1-7, 2019.

SUMMARY THOUGHTS



Dr. William J. Kroll

**World famous Metallurgist and Benefactor of the Colorado School of Mines.
Inventor of commercial processes for the production of titanium and
zirconium. Philanthropist and advocate for Metallurgical education.**

SUMMARY THOUGHTS

KROLL'S DESCENDANTS



“I am happy that a gracious fate has allowed me to carry, for a while, the flag of rare metals research, around which many young people have now gathered to carry on where I have left off “
1943 Perkin Award Acceptance Speech Final Statement by Dr. Kroll

Conclusion

It was a privilege and pleasure to present this.

**I am glad to take any questions and
answer some of them 😊**

Thank you !

The Kroll Institute for Extractive Metallurgy

45 Years of Success in Research and Education

Dr. Corby G. Anderson
Harrison Western Professor

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