Critical Minerals as By-Products of Production and Criticality in Intellectual Capital

NOVEMBER 20, 2020

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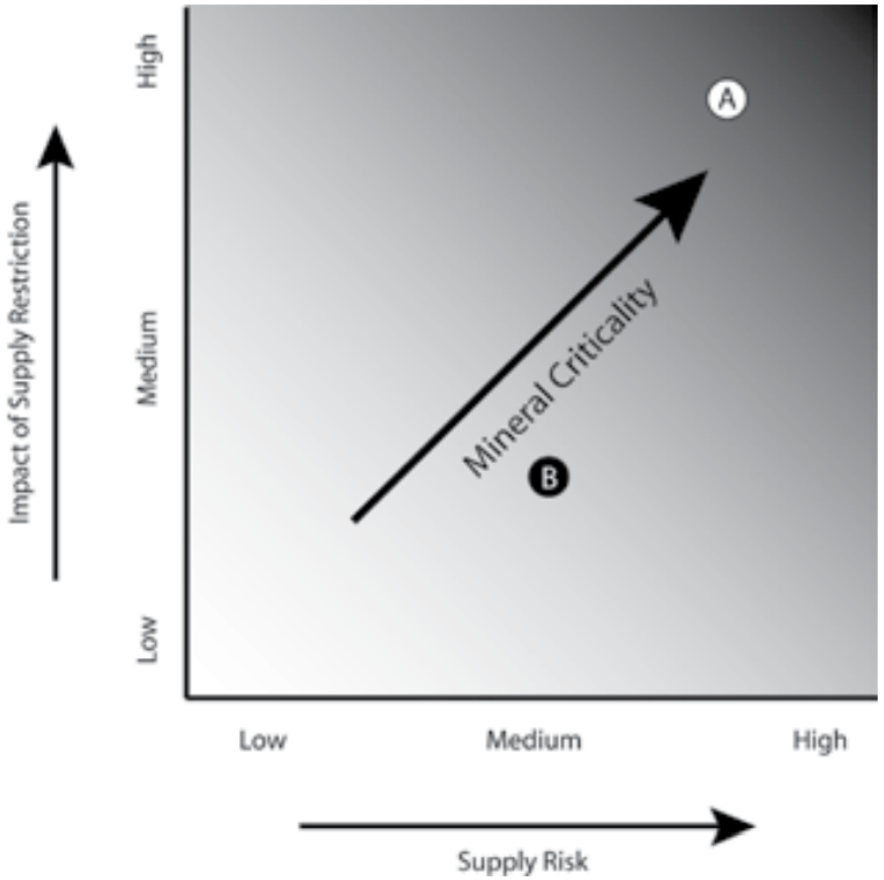


What defines criticality?

- Executive Order #13817:
  - "A non-fuel mineral or mineral material essential to the economic and national security of the United States
  - "The supply chain of which is vulnerable to disruption, and
  - "That serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security"

L. T. Espinoza and C. Gandenberger, "Critical raw materials and the EU," pp. 737–745.

Guidelines for Critical Mineral List

Screening method for critical materials list made up of 2 primary indicators:

- Minerals which exhibit a high Herfindahl-Hirschman Index (HHI)
  - >2,500
- Minerals with a high net import reliance
  - >50%
- Minerals in list are included based on one metric or another

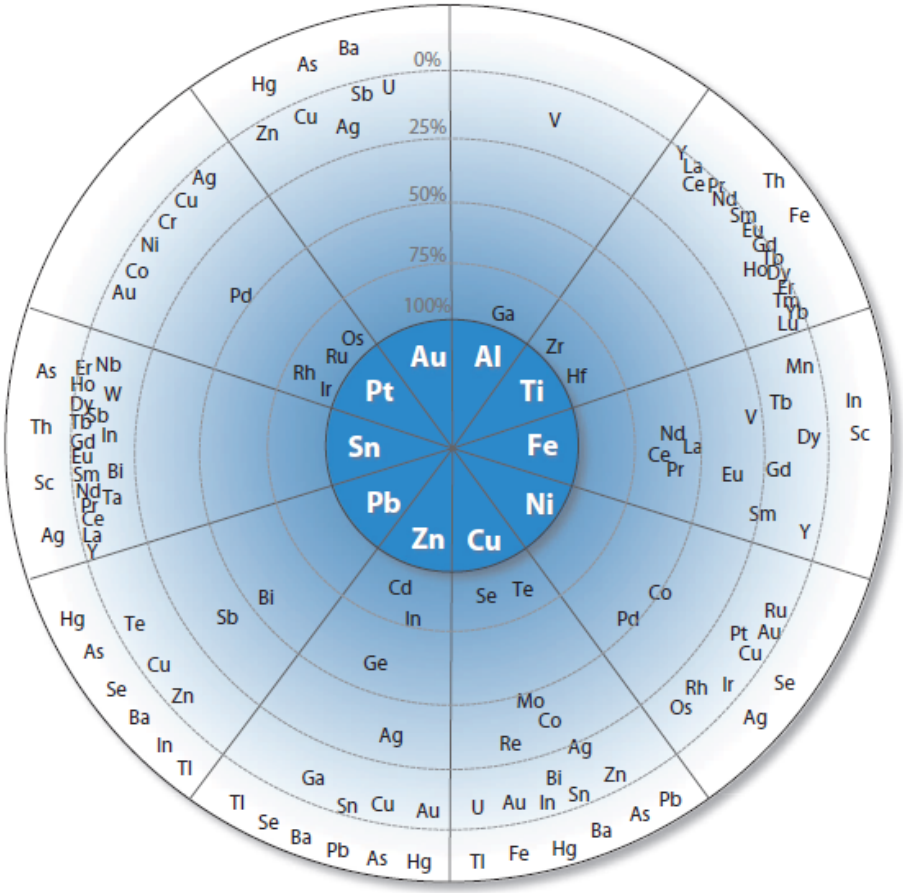
[X, applicable sector; --, not applicable]

Mineral commodity	Sectors						Top producer	Top supplier	Notable example application
	Aerospace (nondefense)	Defense	Energy	Telecommunications and electronics	Transportation (nonaerospace)	Other			
Aluminum	X	X	X	X	X	X	China	Canada	Aircraft, power transmission lines, lightweight alloys.
Antimony	--	X	X	X	X	X	China	China	Lead-acid batteries.
Arsenic	--	X	X	X	--	X	China	China	Microwave communications (gallium arsenide).
Barite	--	--	X	X	--	X	China	China	Oil and gas drilling fluid.
Beryllium	X	X	X	X	--	X	United States	Kazakhstan	Satellite communications, beryllium metal for aerospace.
Bismuth	--	X	X	X	--	X	China	China	Pharmaceuticals, lead-free solders.
Cesium and rubidium	X	X	X	X	--	X	Canada	Canada	Medical applications, global positioning satellites, night-vision devices.
Chromium	X	X	X	X	X	X	South Africa	South Africa	Jet engines (superalloys), stainless steels.
Cobalt	X	X	X	X	X	X	Congo[1] (Kinshasa)	Norway	Jet engines (superalloys), rechargeable batteries.
Fluorspar	--	--	X	X	--	X	China	Mexico	Aluminum and steel production, uranium processing.
Gallium	X	X	X	X	--	X	China	China	Radar, light-emitting diodes (LEDs), cellular phones.
Germanium	X	X	X	X	--	X	China	China	Infrared devices, fiber optics.
Graphite (natural)	X	X	X	X	X	X	China	China	Rechargeable batteries, body armor.
Helium	--	--	--	X	--	X	United States	Qatar	Cryogenic (magnetic resonance imaging [MRI]).
Indium	X	X	X	X	--	X	China	Canada	Flat-panel displays (indium-tin-oxide), specialty alloys.
Lithium	X	X	X	X	X	X	Australia	Chile	Rechargeable batteries, aluminum-lithium alloys for aerospace.
Magnesium	X	X	X	X	X	X	China	China	Incendiary countermeasures for aerospace.
Manganese	X	X	X	X	X	X	China	South Africa	Aluminum and steel production, lightweight alloys.
Niobium	X	X	X	X	--	X	Brazil	Brazil	High-strength steel for defense and infrastructure.
Platinum group metals[2]	X	--	X	X	X	X	South Africa	South Africa	Catalysts, superalloys for jet engines.
Potash	--	--	X	X	--	X	Canada	Canada	Agricultural fertilizer.
Rare earth elements[3]	X	X	X	X	X	X	China	China	Aerospace guidance, lasers, fiber optics.
Rhenium	X	--	X	X	--	X	Chile	Chile	Jet engines (superalloys), catalysts.
Scandium	X	X	X	X	--	X	China	China	Lightweight alloys, fuel cells.
Strontium	X	X	X	X	X	X	Spain	Mexico	Aluminum alloys, permanent magnets, flares.
Tantalum	X	X	X	X	--	X	Rwanda	China	Capacitors in cellular phones, jet engines (superalloys).
Tellurium	--	X	X	X	--	X	China	Canada	Infrared devices (night vision), solar cells.
Tin	--	X	--	X	--	X	China	Peru	Solder, flat-panel displays (indium-tin-oxide).
Titanium	X	X	X	X	--	X	China	South Africa	Jet engines (superalloys) and airframes (titanium alloys), armor.
Tungsten	X	X	X	X	--	X	China	China	Cutting and drilling tools, catalysts, jet engines (superalloys).
Uranium	X	X	X	--	--	X	Kazakhstan	Canada	Nuclear applications, medical applications.
Vanadium	X	X	X	X	--	X	China	South Africa	Jet engines (superalloys) and airframes (titanium alloys), high-strength steel.
Zirconium and hafnium	X	X	X	X	--	X	Australia	China	Thermal barrier coating in jet engines, nuclear applications.

[1]Democratic Republic of the Congo.

[2]This category includes platinum, palladium, rhodium, ruthenium, iridium, and osmium.

[3]This category includes yttrium and the lanthanides.



Host Elements

- Center represents the host element
- Surrounding elements are at a position proportional to the percentage of production linked to the associated host element

N. T. Nassar, T. E. Graedel, and E. M. Harper, "By-product metals are technologically essential but have problematic supply," no. April, pp. 1–11, 2015.

Byproduct vs. Coproduct vs. Primary Production

Byproduct:

- Minor material unable to make project economic

Coproduct:

- Minor material could make project economic, but is still recovered with another product

Primary:

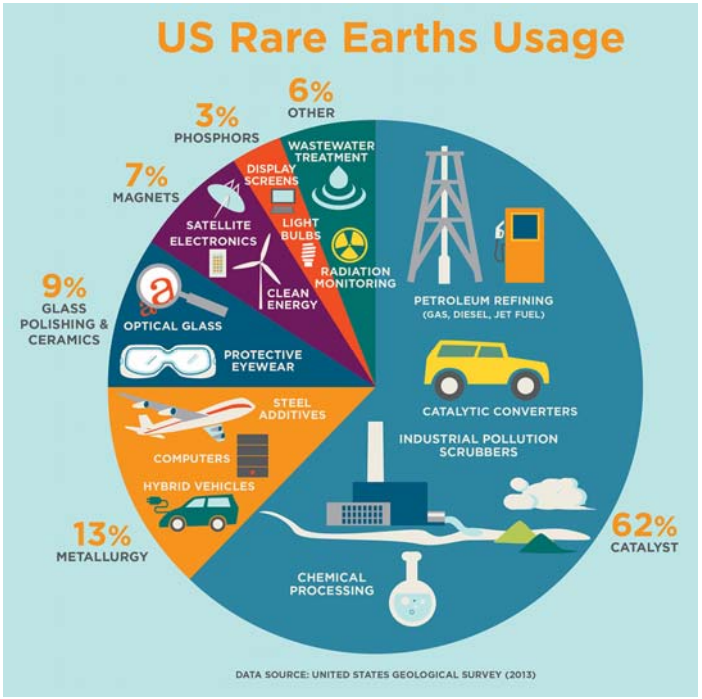
- Primary material which makes the project economic

Elements of Interest

RARE EARTH ELEMENTS

COBALT

INDIUM



https://www.jics.tennessee.edu/files/images/rare-earths-infographic-rev.jpg

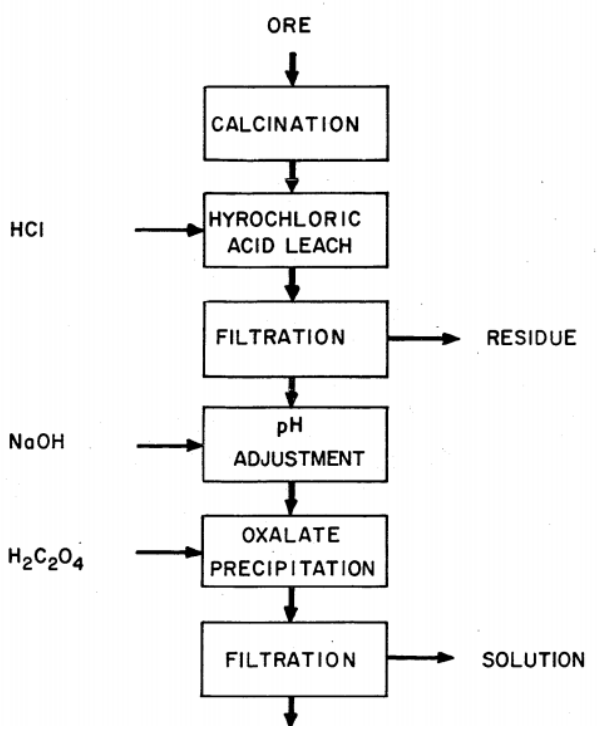
Rare Earth Elements

- Currently mined as a byproduct, coproduct, and primary product around the world
- Import sources for REE compounds and metals
  - China, 80%
  - Estonia, 6%
  - Japan and Malaysia, 3% each
- The U.S. produced 26,000 tons of bastnaesite concentrates in 2018
- Bastnaesite – $(REE)CO_3F$
- Monazite – $(REE)PO_4$

U.S. Geological Survey. "Mineral Commodity Summaries 2019." *Mineral Commodity Summaries*, 2019, doi:10.1007/978-3-540-47108-0-4.

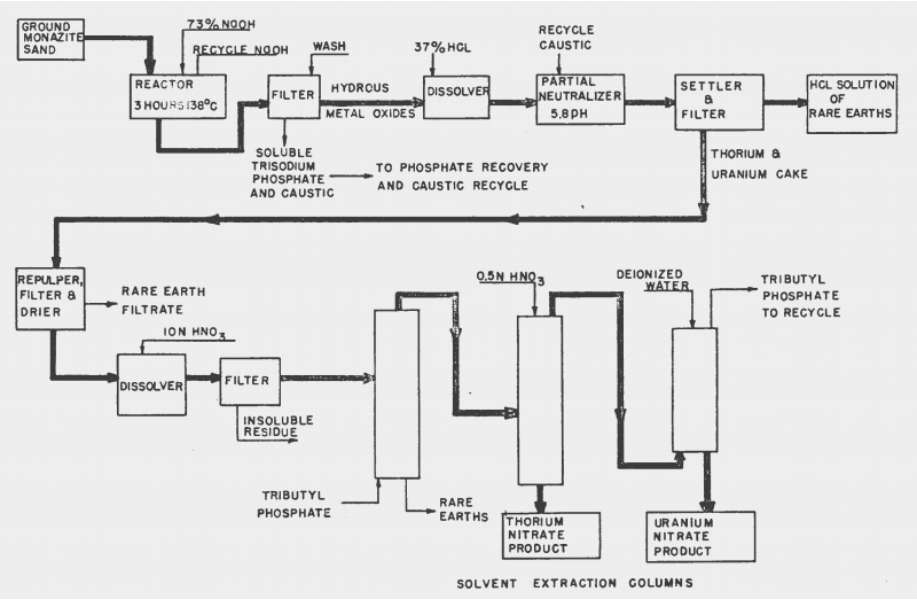
Rare Earth Element Processing - Bastnaesite

- Largest producer, Bayan Obo, produces iron as primary product
  - Bastnaesite concentrate is generated as a product of a gravity separation plant before flotation and extraction
- The sole domestic producer in Mountain Pass, CA produces bastnaesite concentrate as a primary product
  - Average grade greater than 8%
  - Flotation before extraction



Baroch, Charles Joseph, "Processing of California bastnasite ore " (1958). Retrospective Theses and Dissertations. 2244. https://lib.dr.iastate.edu/rtd/2244

Rare Earth Element Processing - Monazite

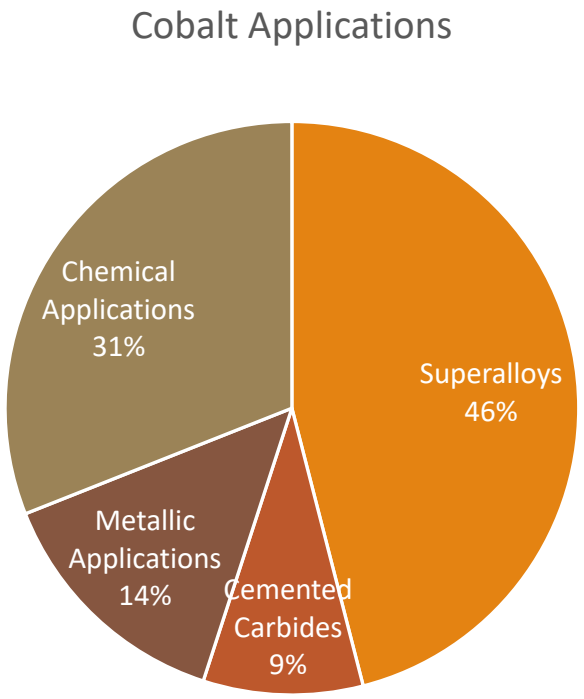


- Research into domestic production of monazite is underway
- Energy Fuels Resources Inc. recently produced its first pilot scale REE carbonate concentrate from North American monazite sands
- Two primary methods for processing:
  - Caustic crack method
  - Sulfuric acid method

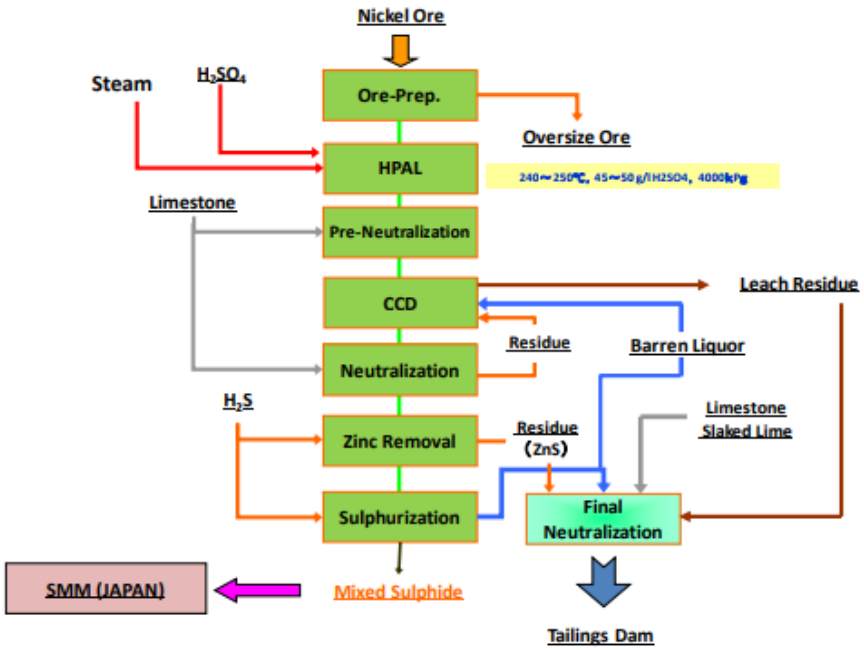
Barghusen, John J. and Smutz, M., "Processing of monazite sands" (1957). Ames Laboratory ISC Technical Reports. 178. http://lib.dr.iastate.edu/ameslab_iscreports/178

Cobalt

- As of 2019, the US has a 78% net import reliance
- Import Sources
  - Norway, 17%
  - Japan, 13%
  - China, 11%
  - Canada, 11%
  - Other, 48%



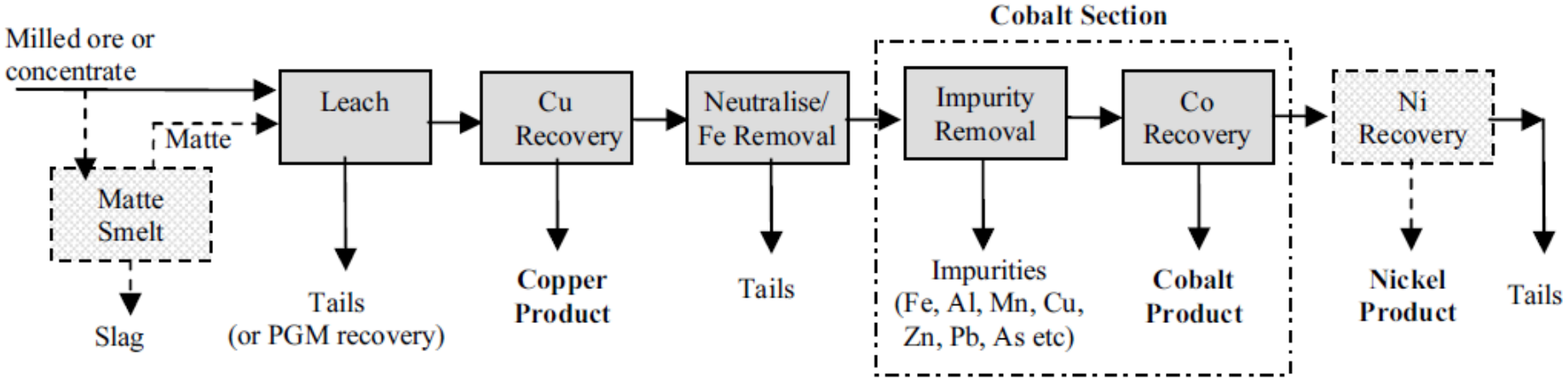
USGS. "Mineral Commodity Summaries - Cobalt." *Mineral Commodity Summaries*, 2020, doi:http://dx.doi.org/10.3133/70140094.



Cobalt Processing

- Produced as a primary product and byproduct of other metals
- Vast majority of cobalt resources are in:
  - sediment-hosted stratiform copper deposits in Congo and Zambia
  - Nickel-bearing laterite deposits in Australia and nearby island countries
  - Magmatic nickel-copper sulfide deposits in mafic and ultramafic rocks in Australia, Canada, Russia, and United States
  - Deep sea nodules in Atlantic, Indian and Pacific Oceans

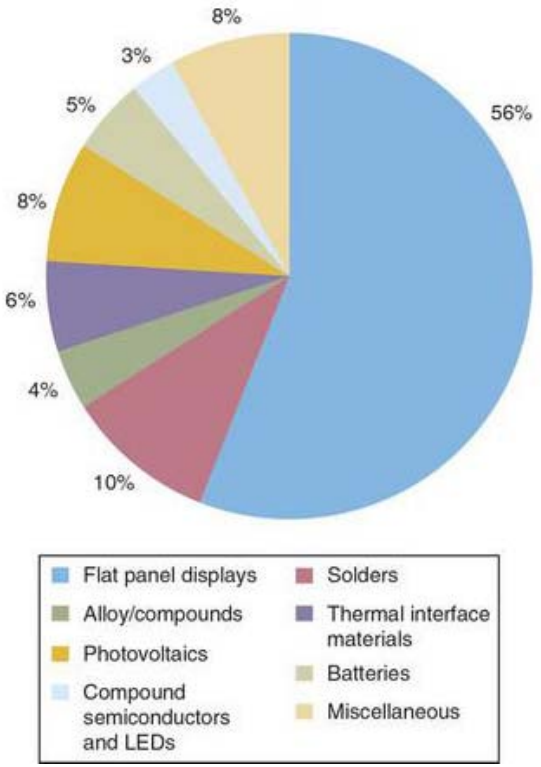
K. G. Fisher, "COBALT PROCESSING DEVELOPMENTS," pp. 237–258, 2011



Cobalt from Copper

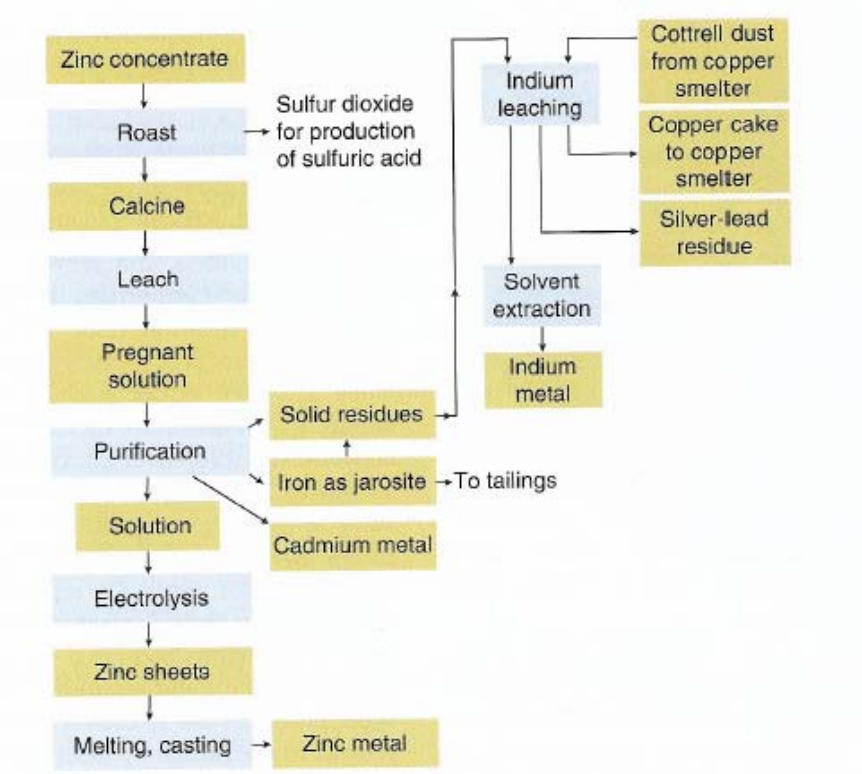
Indium

- Primarily recovered as a byproduct of the zinc-sulfide ore sphalerite
- Indium content in zinc deposits ranges from <1 ppm to 100 ppm
- US currently has a 100% import reliance
- Import sources:
  - China, 36%
  - Canada, 22%
  - Republic of Korea, 11%
  - Taiwan, 7%
  - Other, 24%



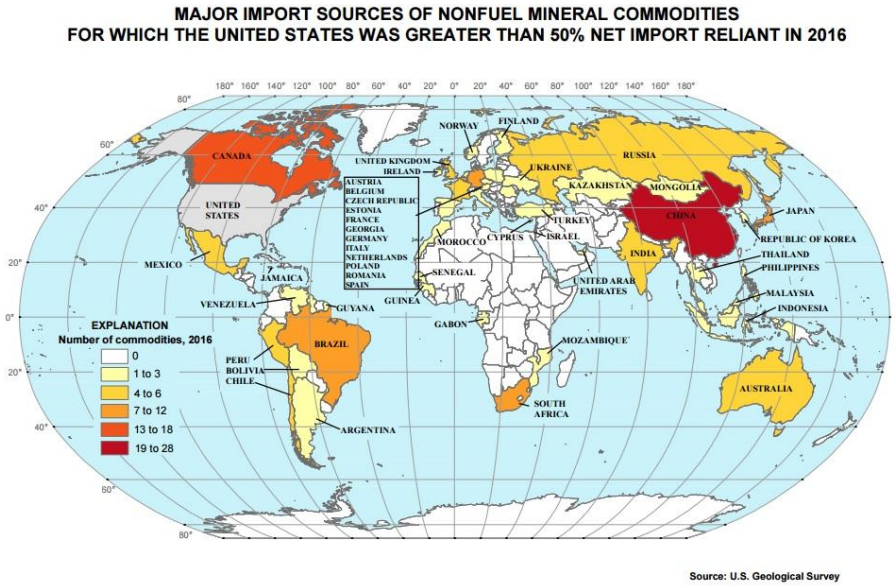
U.S. Geological Survey, "Mineral Commodity Summaries - Indium," *Miner. Commod. Summ.*, 2020.

Indium Recovery from Zinc Ore



U. Schwarz-Schampera, "Chapter 9 - Indium," in *Critical Metals Handbook*, First Edit., G. Gunn, Ed. Chichester: John Wiley & Sons, Ltd., 2014, pp. 204–229.

Conclusion



I would like to acknowledge the support of the Critical Materials Institute. More information on the CMI can be found at: https://www.ameslab.gov/cmi/

THE CRITICAL ASPECT OF CRITICAL MINERALS AND METALS

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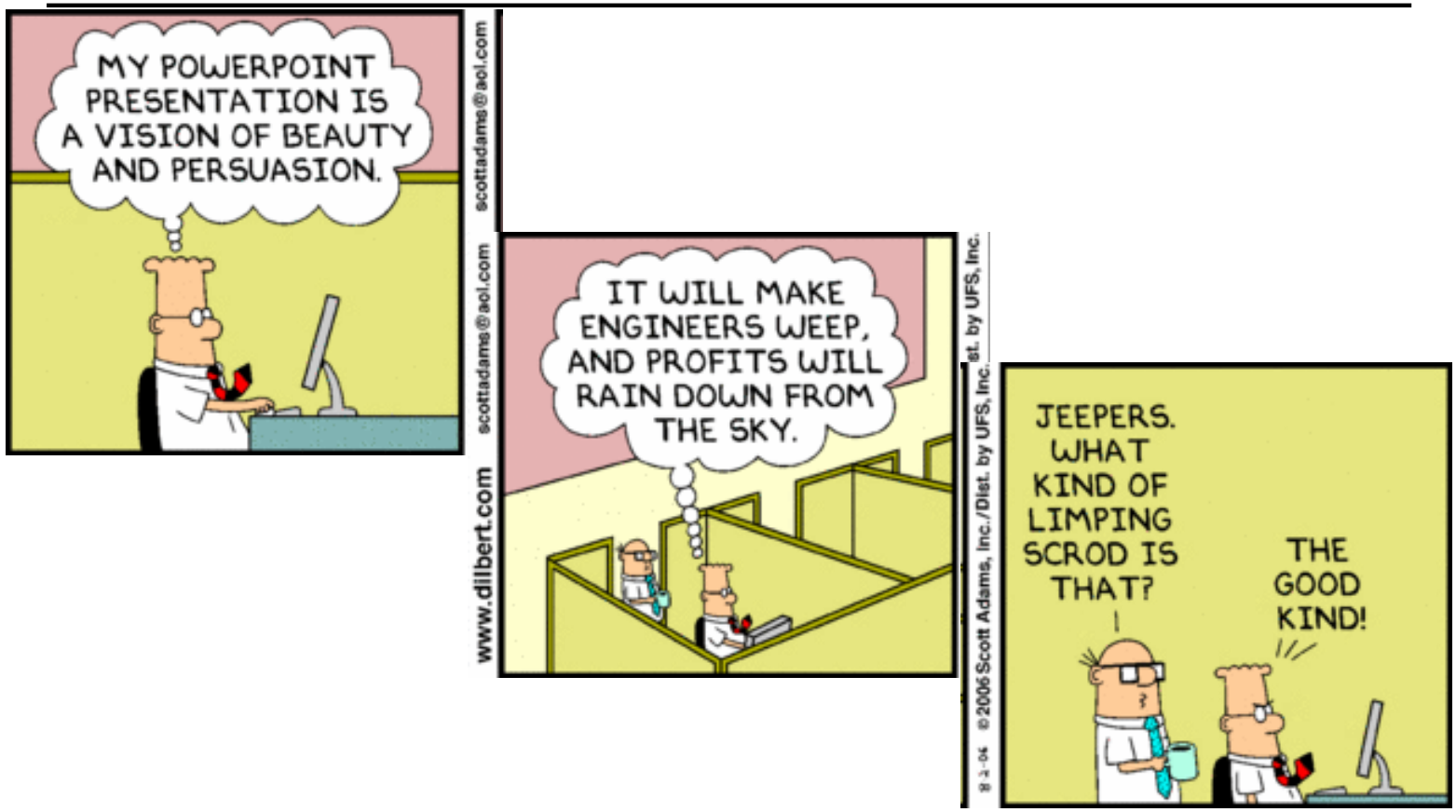
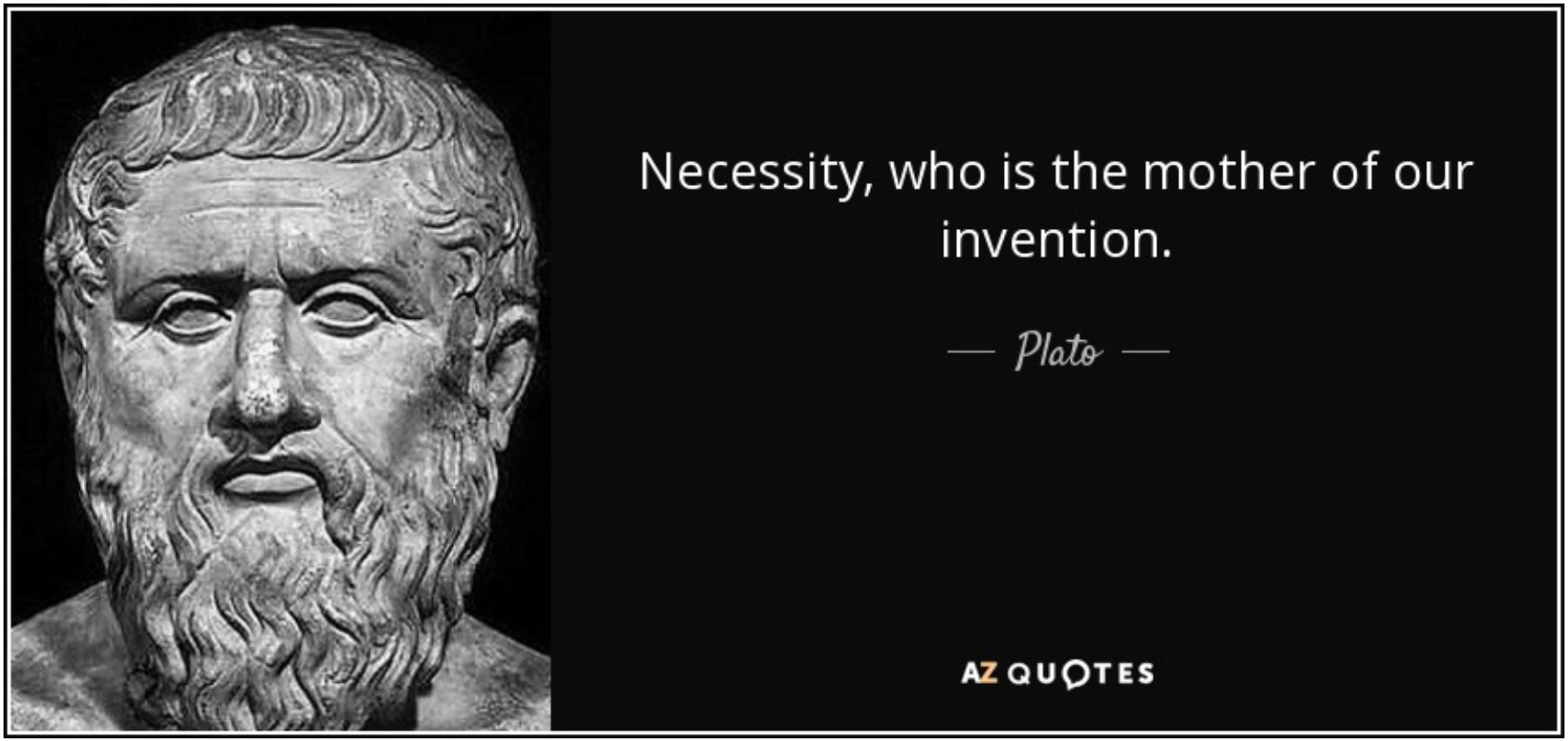
PROFESSIONAL PRESENTATION PHILOSOPHY



MY INITIAL THOUGHTS



MY INITIAL THOUGHTS

The Bronze Age

Metals were first used in tools and weapons manufacture.

Pure copper and bronze, an alloy of copper and tin, were used indiscriminately at first; this early period is sometimes called the Copper Age and it occurred around 4000 B.C.

The development of a metallurgical industry coincided with the rise of urbanization.

The organized operations of mining, smelting, and casting undoubtedly required the specialization of labor and the production of surplus food to support a class of artisans.

The search for raw materials stimulated the exploration and colonization of new territories.

MY INITIAL THOUGHTS

The Iron Age

The casting of iron did not become technically useful until the Industrial Revolution.

The Iron Age developed the basic economic innovations of the Bronze Age and laid the foundations for feudal organization.

They utilized the crops and domesticated animals introduced earlier from the Middle East. Ox-drawn plows and wheeled vehicles acquired a new importance and changed the agricultural patterns.

For the first time humans were able to exploit efficiently the temperate forests. Villages were fortified, warfare was conducted on horseback and in horse-drawn chariots, and alphabetic writing based on the Phoenician script became widespread.

Distinctive art styles in metal, pottery, and stone characterized many Iron Age cultures.

MY INITIAL THOUGHTS

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

MY INITIAL THOUGHTS

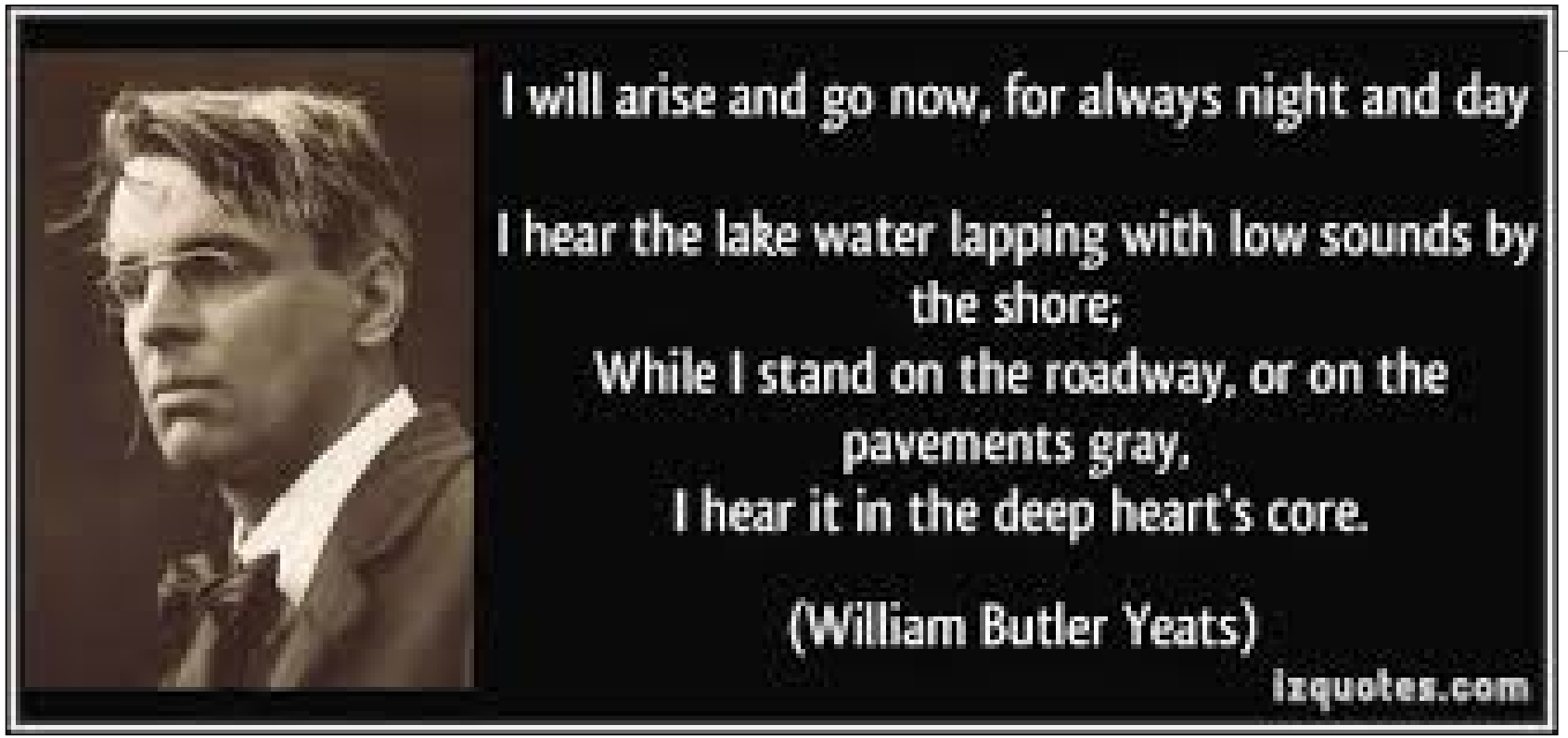
"KIEM - Excellence in Education and Research for the Mining, Minerals and Metals Industries"

- **History**: ***The Kroll Institute for Extractive Metallurgy was established at the Colorado School of Mines in 1974 using a bequest from Dr. William J. Kroll after he died.***
- ***This effort was led by Professor Al Schlechten. For over 45 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.***

The presentation of the first William J. Kroll Zirconium Medal to Admiral H. G. Rickover by Professor A. W. Schlechten, Director of the Kroll Institute for Extractive Metallurgy in 1975.

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.

SUMMARY THOUGHTS AND CONCLUSIONS



SUMMARY THOUGHTS

- **Innovation in Mineral Processing and Extractive Metallurgy has had significant impacts on humanity.**
- **It created the Iron and Bronze ages and civilization as we know it.**
- **It created new materials and new industries like aluminum and titanium.**
- **It has often been created for a need other than it actually found use in.**
- **It was always created by people willing to put perspiration into the effort, overcome failures and accept a risky challenge.**
- **It was not always rewarded by wealth or fame and often met rejection.**
- **So, how do we continue to Innovate in Mineral Processing and Extractive Metallurgy ?**

SUMMARY THOUGHTS

Why would anyone be a Professor ? Why do you do research ?
Are you now retired ? What do you do with your summers off ?

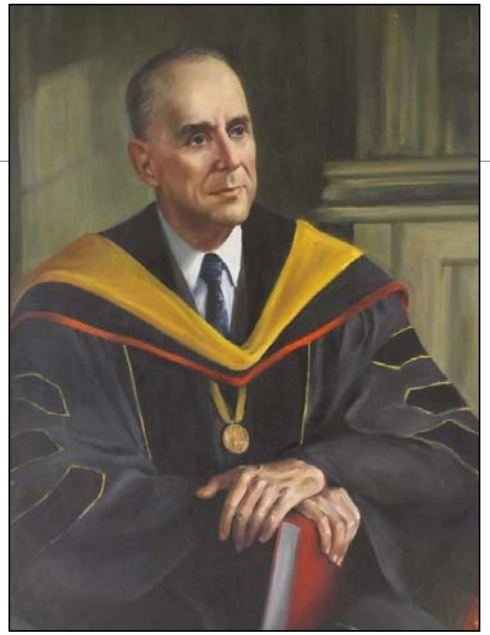
Sacred Heart Catholic Church, Castletownbere, County Cork

built in 1907 **AFTER** mass emigration to Butte, America circa 1872.

"The meaning of life is to find your gift. The purpose of life is to give it away."

Pablo Picasso

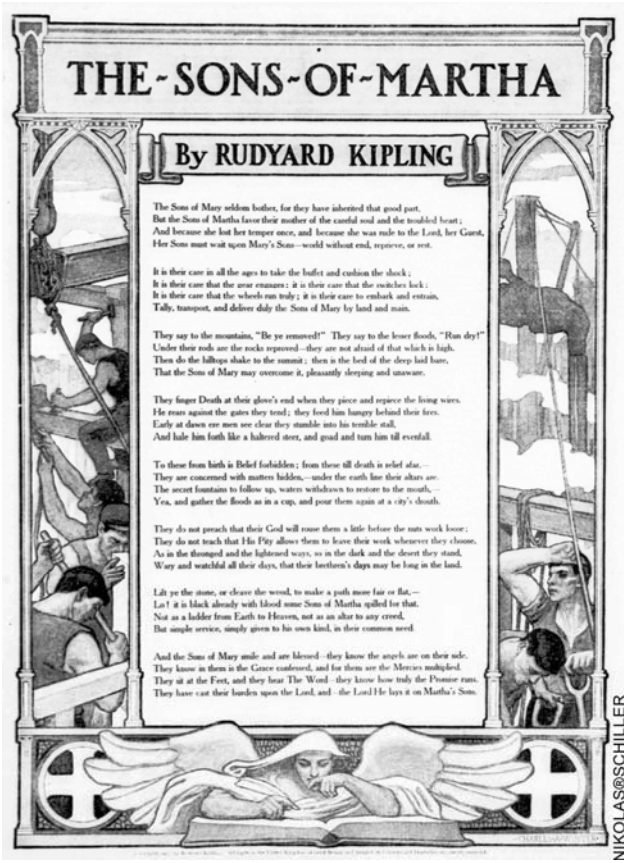
SUMMARY THOUGHTS



Dr. William J. Kroll

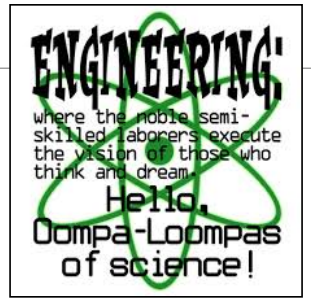
World famous Metallurgist and Benefactor of the Colorado School of Mines. Inventor of commercial processes for the production of titanium and zirconium. Philanthropist and advocate for Metallurgical education.

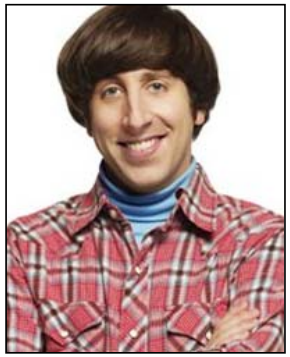
SUMMARY THOUGHTS



The **Sons of Martha** is a poem written by Rudyard Kipling who admired engineers. It is inspired by the biblical story of Jesus at the home of Martha and Mary. It celebrates the careful work done by engineers and builders like Martha to provide for others physical needs. In the Bible story, Christ visits a home where two sisters, Mary and Martha, live. Mary sits nobly at the visitor's feet to listen to him while Martha races about attending to the hospitality until her patience runs out, and Martha calls on Jesus to direct Mary to help her. Jesus chides Martha for her mundane concerns and is told: "Mary has chosen what is better". It is recited at US and Canadian Engineering Order Inductions.

SUMMARY THOUGHTS



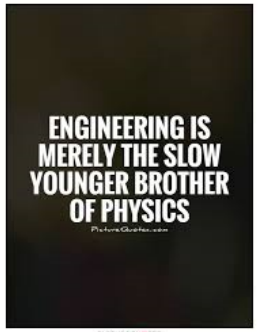


Howard
A Son of Martha

And the Sons of Mary smile and are blessed---they know the Angels are on their side.

They know in them is the Grace confessed, and for them are the Mercies multiplied.

They sit at the feet---they hear the Word---they see how truly the Promise runs.
They have cast their burden upon the Lord, and---the Lord He lays it on Martha's Sons !



Sheldon
A Son of Mary

SUMMARY THOUGHTS

- **There are about 8 US schools left that teach and research Mineral Processing and about 5 that teach and research any Extractive Metallurgy.**
- **There is no distinct degree in Mineral Processing or Extractive Metallurgy offered any longer in North America.**
- **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.**

SUMMARY THOUGHTS

- **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.**
- **The majority of the Western world mineral research is done by the METS service sector.**
- **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 an equally large but separate school !

SUMMARY THOUGHTS

So, Rare Earths are not Rare at all.
In the USA, Mineral Processing and Extractive Metallurgy are very Rare.
The Chinese now control what the USA had created in Rare Earths because they control now Mineral Processing and Extractive Metallurgy.

SUMMARY THOUGHTS

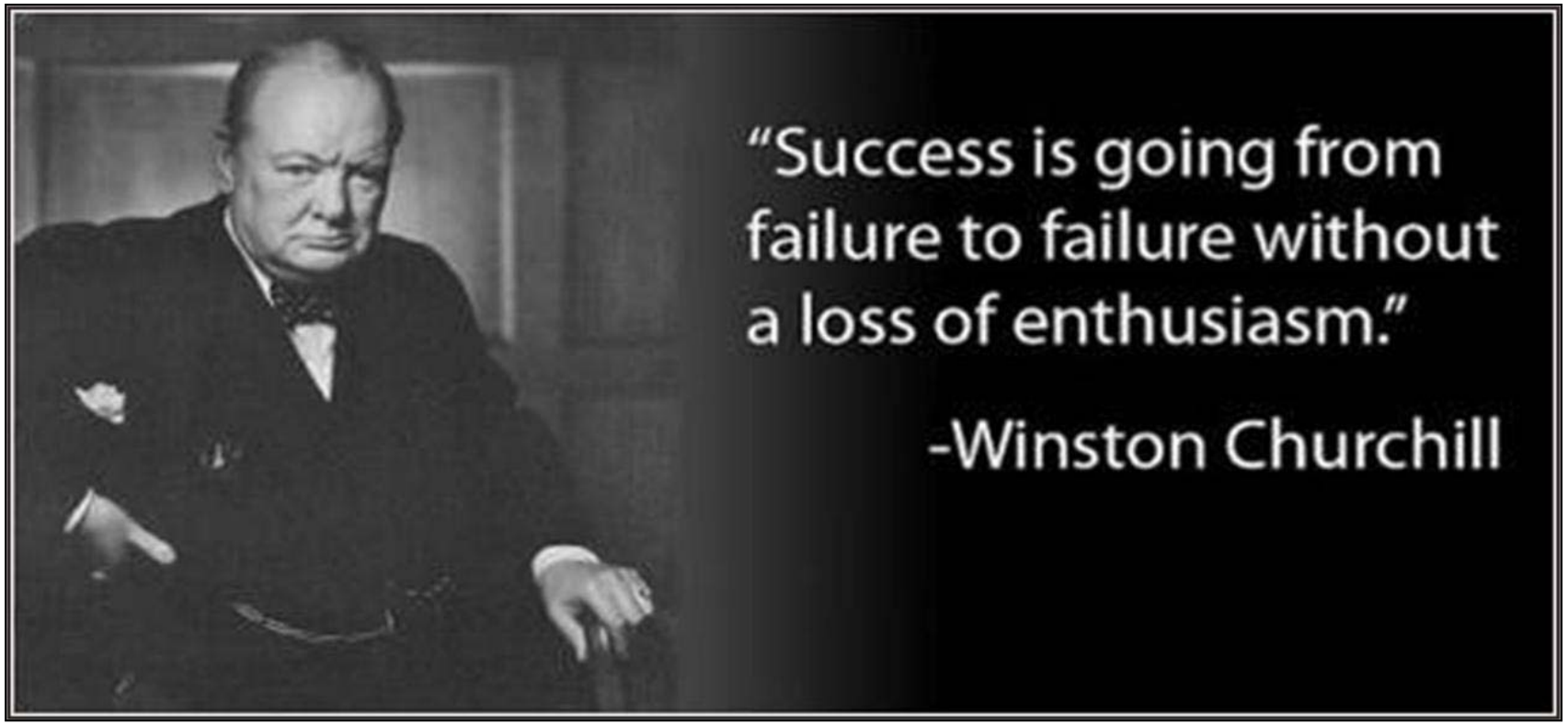
- **The world's growing population needs a vast amount of future skilled mineral and metallurgical engineering professionals to provide the additional global minerals and metals demands.**
- **Where will be doing innovative research in 20 years ?**
- **Who will provide the increasing minerals and metals and the innovations needed to produce them more efficiently from more complex, lower grade and more remote orebodies ?**
- **Who will create entirely new metal industries like Kroll did ?**
- **Who will create an enduring educational and research legacy as Kroll did ?**

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

INNOVATION IN MINERAL PROCESSING AND EXTRACTIVE METALLURGY



CONCLUSION

It was a privilege and pleasure to present this.

I am glad to take any questions and

answer …….. some of them ☺

Thank you !