SEPARATION SCIENCE AND TECHNOLOGY EDUCATION:
EXTRACTIVE METALLURGY PERSPECTIVE

Dr. Corby G. Anderson
Harrison Western Professor
The Kroll Institute for Extractive Metallurgy
Colorado School of Mines

Colorado School of Mines

- Est. 1874
- Golden, Colorado
- 21 majors
- 193 Faculty
- 4300 students
- “...have a unique mission in energy, mineral, and materials science and engineering…”
- “has the most stringent admission standards of any US public engineering school.”
- “Average starting salary of a BSc Mines graduate is $10 K more than an Ivy League graduate.”

G. S. ANSELL DEPARTMENT OF METALLURGICAL & MATERIALS ENGINEERING
The Kroll Institute for Extractive Metallurgy

Dr. Patrick R. Taylor, Director KIEM
George S. Ansell Department of Metallurgical & Materials Engineering, Colorado School of Mines

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.

History: The Kroll Institute for Extractive Metallurgy was established at the Colorado School of Mines in 1974 using a bequest from William J. Kroll.

This effort was led by Professor Al Schlechten. 40 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.

“KIEM - Excellence in Education and Research for the Mining, Minerals and Metals Industries”
ALUMINUM
A RARE METAL BEFORE 1887

The 10 Most Abundant Elements in the Earth's Crust

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance percent by weight</th>
<th>Abundance parts per million by weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>46.1%</td>
<td>461,000</td>
</tr>
<tr>
<td>Silicon</td>
<td>28.2%</td>
<td>282,000</td>
</tr>
<tr>
<td>Aluminum</td>
<td>8.23%</td>
<td>82,300</td>
</tr>
<tr>
<td>Iron</td>
<td>5.63%</td>
<td>56,300</td>
</tr>
<tr>
<td>Calcium</td>
<td>4.15%</td>
<td>41,500</td>
</tr>
<tr>
<td>Sodium</td>
<td>2.36%</td>
<td>23,600</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.33%</td>
<td>23,300</td>
</tr>
<tr>
<td>Potassium</td>
<td>2.09%</td>
<td>20,900</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.565%</td>
<td>5,650</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0.14%</td>
<td>1,400</td>
</tr>
</tbody>
</table>
Karl Joseph Bayer

Chateau Des Beaux, France
ALUMINUM
A COMMON METAL AFTER 1887

Figure 10.1: Tonnage of bauxite treated annually.

CRITICAL MATERIALS
Rare Earths

Antimony
CRITICAL MATERIALS

Rare Earths

As of 2009, the USGS reports the distribution of rare earths by end use, in decreasing order, was:

- chemical catalysts 22%
- metallurgical applications and alloys 21%
- petroleum refining catalysts 14%
- automotive catalytic converters 13%
- glass polishing and ceramics 9%
- rare earth phosphors for computer monitors, lighting, televisions 8%
- permanent magnets 7%
- electronics 3%
- others 3%

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Rare Earths

- Total TREO abundance in earth is 220 ppm. Carbon 200 ppm!
- They are widely distributed in low individual concentrations but found all together normally.
- There are 123 important rare earth deposits in the world and they are located in twenty countries.
- They occur in over 200 minerals.
- 95% of TREOs occur in the minerals bastansite, monazite and xenotime.

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Rare Earths

Powderhorn White Earth Deposit
Gunnison, Colorado - Perovskite, CaTiO₃

500 Million Tons of 8% Perovskite - 0.36% TREO!
Development (hence rarity) of Ti and TREO impeded by concentration and separation not availability!

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Example Flow Sheet – Mineral Processing – Flotation and Chemical Treatment

A very complex flow sheet that requires significant energy and chemicals. Research may lead to alternative surface chemistry and flotation processes.

Figure 3.9 Simplified flowsheet for the recovery of bastnaesite at the Molyovat plant (Aqtil 1988).

Rare Earths Hydrometallurgy

- Rare earths are difficult to separate as they have very similar chemical natures.

- Took 160 years for scientists to isolate and identify all of them.

- They have ‘lanthanide contraction’ which is the root cause of rare earth chemistry similarities.
Figure 1.2  Lanthanide contraction.
Selective Hydrometallurgical IX Separation of REO


Typical Yields and Purities Of The Rare Earth Oxides Recovered Through Ion Exchange.

Separation of the Lanthanides from Cationic Exchanger DOWEX50 with 1 M Lactate pH = 3.19, flow rate at 0.4 ml/cm²/min.

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Extraction of REO from Bastnasite

Once a concentrate is obtained, then the metals of interest must be extracted from the material. Several approaches are possible, usually involving calcining and acid leaching. The solutions are then subjected to ion exchange or solvent extraction for purification.

Figure 3.15 Chemical processing of bastnasite.
Antimony History

- Known in 4000 B.C.
- Metal known as regulus
- Greek for “metal not found alone”
- Metal is brittle - must be alloyed
- Early 1900’s used in munitions
- Automobile batteries boosted usage
- Flame retardants now major use
Antimony Occurrence and Mineralogy

- Abundance in earth 0.2 g/t
- Antimony is a chalcophile
- Over 100 Antimony minerals are known
- Stibnite, $\text{Sb}_2\text{S}_3$, is the predominant ore

Table 1. Common Primary Antimony Minerals.

<table>
<thead>
<tr>
<th>Horsfordite Cu$_3$Sb</th>
<th>Dyerasite Ag$_3$Sb</th>
<th>Stibiodomykite Cu$_3$(As,Sb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurostibite Au$_3$Sb$_2$</td>
<td>Breithauptite Ni$_3$Sb</td>
<td>Arite Ni(As,Sb)</td>
</tr>
<tr>
<td>Ullmanite Ni$_3$Sb$_6$</td>
<td>Gadmundite Fe$_3$Sb$_6$</td>
<td>Stibnite $\text{Sb}_2\text{S}_3$</td>
</tr>
<tr>
<td>Stibiobismuthine (Bi, Sb)$_5$S$_7$</td>
<td>Tetraedrite Cu$_4$Sb$_6$S$_6$</td>
<td>Annivite Cu$_{12}$(Sb,Bi,As)$<em>6$S$</em>{13}$</td>
</tr>
<tr>
<td>Freibergite (Cu,Ag)$_3$Sb$_3$S$_3$</td>
<td>Bournonite PbCuSb$_3$</td>
<td>Stephanite Ag$_5$Sb$_4$</td>
</tr>
<tr>
<td>Ramdohrite Ag$_3$Pb$_2$Sb$_2$S$_4$</td>
<td>Andorite Ag$_3$Pb$_2$Sb$_2$S$_4$</td>
<td>Geocronite Pb$_4$(As,Sb)$_2$S$_6$</td>
</tr>
<tr>
<td>Zinckenite Pb$_3$Sb$_2$S$_4$</td>
<td>Jamesonite, Pb$_4$Fe$_2$Sb$_4$S$_4$</td>
<td>Boulangerite Pb$_3$Sb$_2$S$_3$</td>
</tr>
<tr>
<td>Falkmanite Pb$_3$Sb$_2$S$_4$</td>
<td>Meneghinite Pb$_3$Sb$_2$S$_4$</td>
<td>Cylindrite Pb$_3$Sb$_2$S$_3$</td>
</tr>
<tr>
<td>Franckeite Pb$_3$Sb$_2$Sb$_2$S$_4$</td>
<td>Livingstonite HgSb$_3$S$_7$</td>
<td>Berthierite Fe$_2$Sb$_2$S$_4$</td>
</tr>
<tr>
<td>Famatinite Cu$_3$Sb$_3$</td>
<td>Stibioluzonite Cu$_3$(Sb,As)$_6$S$_6$</td>
<td>Berthonite Cu$_3$Pb$_2$Sb$_2$S$_6$</td>
</tr>
<tr>
<td>Bolivianite Ag$_3$Sb$_3$S$_10$</td>
<td>Sulfo-antimonite Ag$_3$Pb$_2$Sb$_2$S$_3$</td>
<td>Kermisite Sb$_2$S$_3$</td>
</tr>
<tr>
<td>Stibiotalantalite SbTaO$_4$</td>
<td>Stibiocolumbite Sb$_2$NbO$_4$</td>
<td>Senarmontite Sb$_2$O$_3$</td>
</tr>
<tr>
<td>Romeite 5CaO:3Sb$_2$O$_5$</td>
<td>Stibiconite Sb$_4$O$_7$H$_2$O</td>
<td>Stenhuggarite CaFe$_2$Sb$_3$O$_7$</td>
</tr>
<tr>
<td>Cervantite Sb$_2$O$_4$</td>
<td>Stibio-tellurobismutite B$_{17}$O$\text{SbTe}_7$</td>
<td>Valentinite Sb$_2$O$_3$</td>
</tr>
</tbody>
</table>
Antimony Uses and Applications

- \(\text{Sb}_2\text{O}_3\) for flame retardants, pigments, and catalysts.
- \(\text{NaSb(OH)}_6\) for flame retardants and glass.
- Antimonial lead and alloys.
- \(\text{Sb}_2\text{S}_3\) in brake lines and matches.
- \(\text{Sb}_2\text{O}_5\) for flame retardants.

Antimony

For optical rewritable disks like DVD as a material to phase-change layer providing increase of data capacity.

For polyester fiber as a polymerization catalyst.

For low-noise refrigerators and wine cellars of recent advanced models as a mixture to materials of thermoelectric module of cooling system.

For components of automobile such as an engine block as additives in molding and a brake pad/lining as additives for friction material, for wire coating materials, rubber materials, and for the plastics in automobile interiors for its flame retardant properties.

For its flame retardant properties, antimony is used as an additive in the production of components for office electronic equipment such as personal computers, copying and facsimile machines. For electronic components such as IC filler and IC chips, as a flame retardant.
ANTIMONY
Antimony Market Factors

Global Demand is increasing as the:

Chinese economy continues to grow at approximately 10% per year;

And the Western world is increasing the requirements on fire-proofing.

ANTIMONY

Worldwide known reserves are be only 2.1m tonne of Sb metal.
This represents only 11 years of consumption left.

China has the majority of known metal reserves.
Antimony (Sb – stibnite) is a very scarce mineral

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Economics of Antimony

Few Published Prices

Chinese Dominate for Past 25 Years

Zhao Tian Cong
ANTIMONY

Typical Stibnite Ore
Mineral Processing Results

<table>
<thead>
<tr>
<th>Operation</th>
<th>Ore Grade, % Sb</th>
<th>Conc. Grade, % Sb</th>
<th>Tails Grade, % Sb</th>
<th>Recovery, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand sorting</td>
<td>2.25</td>
<td>7.80</td>
<td>0.12</td>
<td>95.95</td>
</tr>
<tr>
<td>Heavy media</td>
<td>1.58</td>
<td>2.65</td>
<td>0.18</td>
<td>95.11</td>
</tr>
<tr>
<td>Flotation</td>
<td>3.19</td>
<td>47.58</td>
<td>0.21</td>
<td>93.97</td>
</tr>
<tr>
<td>Average</td>
<td>2.68</td>
<td>19.44</td>
<td>0.18</td>
<td>94.11</td>
</tr>
</tbody>
</table>

Pyrometallurgy of Antimony

- Generally grade determines process
- 5 - 25% Sb - volatilized to Sb$_2$O$_3$
- 25 - 40% Sb - smelted in blast furnace
- 45 - 60% Sb - liquation or iron precipitation
Hydrometallurgy of Antimony

- Alkaline Sulfide system
- Acidic Chloride system
Sunshine Antimony Process

CRITICAL ASPECT OF CRITICAL MATERIALS

??????
CRITICAL ASPECT OF CRITICAL MATERIALS

• 50% of All Experienced North American Mineral Engineering Expertise Will Retire In Less Than 10 Years.

• In North America Only About A Half Dozen Schools Teach Or Do Research In Extractive Metallurgy.

• No North American School Offers An Accredited Distinct Mineral Processing Or Extractive Metallurgy Degree.

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CRITICAL ASPECT OF CRITICAL MATERIALS

• There Is Only One Distinct Metallurgical Engineering Program In North America (U of Utah). The Rest Are Aligned With Or Subsets Of Materials Or Other Programs.

• We Have Lost 3 Generations of Mineral Engineering Talent.

• We Lost The US Bureau of Mines.

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CRITICAL ASPECT OF CRITICAL MATERIALS

• We Cannot Attract, Hire Or Retain Qualified Faculty.

• The Western Australia School of Mines Just Consolidated Mining Engineering With Extractive Metallurgy.

• The Camborne School of Mines Just Suspended It’s Mineral Engineering Program.

• We Gave Up Our Mineral Engineering Intellectual Capacity And It Will Take A Long Time And A Lot of Effort To Regain It.

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Critical Materials Institute
AN ENERGY INNOVATION HUB

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.

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Projects at Colorado School of Mines

• Project 1.1.1: Advanced Beneficiation Techniques
• Project 1.2.2: Conversion to Metals, Alloys and Materials
• Project 2.1.4: Thermomagnetic Processing of Rare Earth Magnets
• Project 3.1.1: Recovery and Reuse of Rare Earth Metals from Phosphor Dusts
• Project 3.1.3: Cost Effective Recycling of Rare Earth Containing Magnets
• Project 3.1.4: Beneficiation of Photovoltaic (and other) Functional Coatings
• Project 4.2.1: Treatment of mineral processing waste streams and recovery of clean water using microfiltration systems
• Project 4.3.1: Criticality and sustainability assessment
• Project 4.3.2: Economic analysis of CMI research and global material supply chains

Caelen Anderson is a PhD student. His research involves the Surface Chemistry of Rare Earth Minerals with Dr. Taylor.

Matt Esquibel is a MS student. His research is on the recycling of indium and rare earths from plasma display panels (flat-panel displays) with Dr. Taylor.
KIEM

Daniel Haughey, MS student working on rare earth recovery from thermal spray wastes with Dr. Taylor.

Ben Kronholm, MS student working on TREO ion exchange with Dr. Anderson.

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Patrick Eduafo MS student working on Rare Earth Recovery from Fluorescent lights with Dr. Mishra.

James Wright MS student working on Rare Earth Recovery from magnets lights with Dr. Taylor.
Metallurgical Innovation Philosophy

“Success is going from failure to failure without a loss of enthusiasm.”
-Winston Churchill

Thank You For This Opportunity to Present!

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Hill Hall, home of KIEM
Please come see what we’re up to.

The Kroll Institute for Extractive Metallurgy
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www.mines.edu
QUESTIONS

If you want a copy of the presentation please give me a business card or email me at cganders@mines.edu

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