Critical Materials Institute

AN ENERGY INNOVATION HUB

Industrial Manufacture of By Product Critical Materials

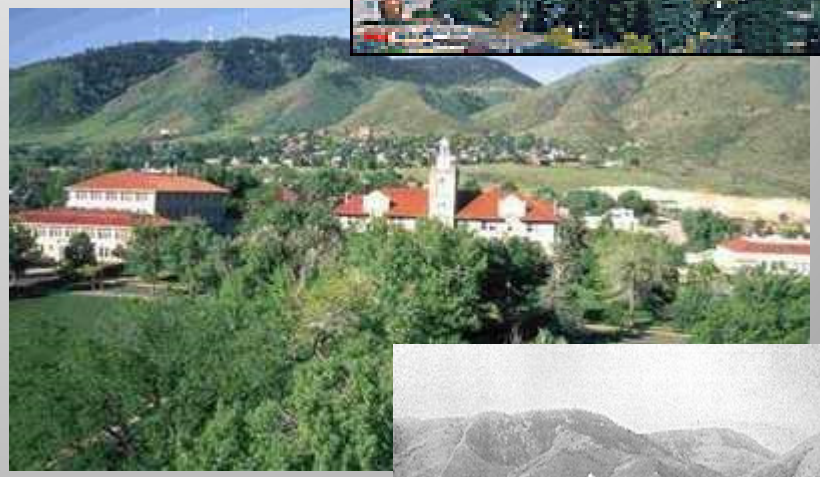
By

Dr. Corby G. Anderson

KIEM
Kroll Institute for
Extractive Metallurgy

Colorado School of Mines

- Est. 1874
- Golden, Colorado
- 3 Colleges & 21 majors
- 200 Faculty
- 5000 Students
- "…has a unique mission in energy, mineral, and materials science and engineering…"
- "has the most stringent admission standards of any US public engineering school."
- "Ranked as #1 Engineering School in the US by USAToday."
- "ranked #1 in the World for Mining and Mineral Engineering."
- "average starting salary of a BSc Mines graduate is $ 10 K more than an Ivy League graduate."



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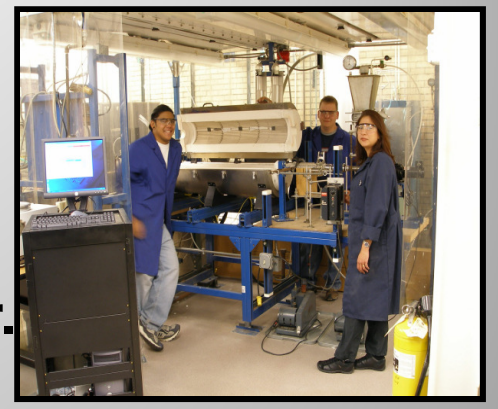
KIEM
Kroll Institute for Extractive Metallurgy

Department of Metallurgical & Materials Engineering - MME

- 20 full time faculty members
- 5 Centers and Institutes:
  - *Kroll Institute for Extractive Metallurgy*
  - Colorado Center for Advanced Ceramics
  - Advanced Steel Processing & Products Res. Ctr.
  - Center for Welding, Joining & Coating Research
  - Advanced Coatings & Surface Engineering Res. Ctr.



- Degrees:
  - PhD, MS, ME & BS in Metallurgical & Materials Engineeri
  - PhD & MS in Materials Science
  - PhD & MS in Nuclear Engineering
- Students:
  - Graduate level : 140
  - Undergraduate level: 50 per year

CMI Critical Materials Institute
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SCHOOL OF MINES 1874 COLORADO

KIEM
Kroll Institute for Extractive Metallurgy

The Kroll Institute for Extractive Metallurgy

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

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Industrial Metal By Product History

A Common Occurrence in the Mining & Metals Industry

Molybdenum is Produced as By Product of Copper

Cobalt is Produced as a By Product of Nickel and Copper

Lead and Zinc are Co Produced Along With Gold and Silver By Products

Indium is a By Product of Zinc Production

Gallium is a By Product of Aluminum Production

Gold and Silver are By Products of Copper Production

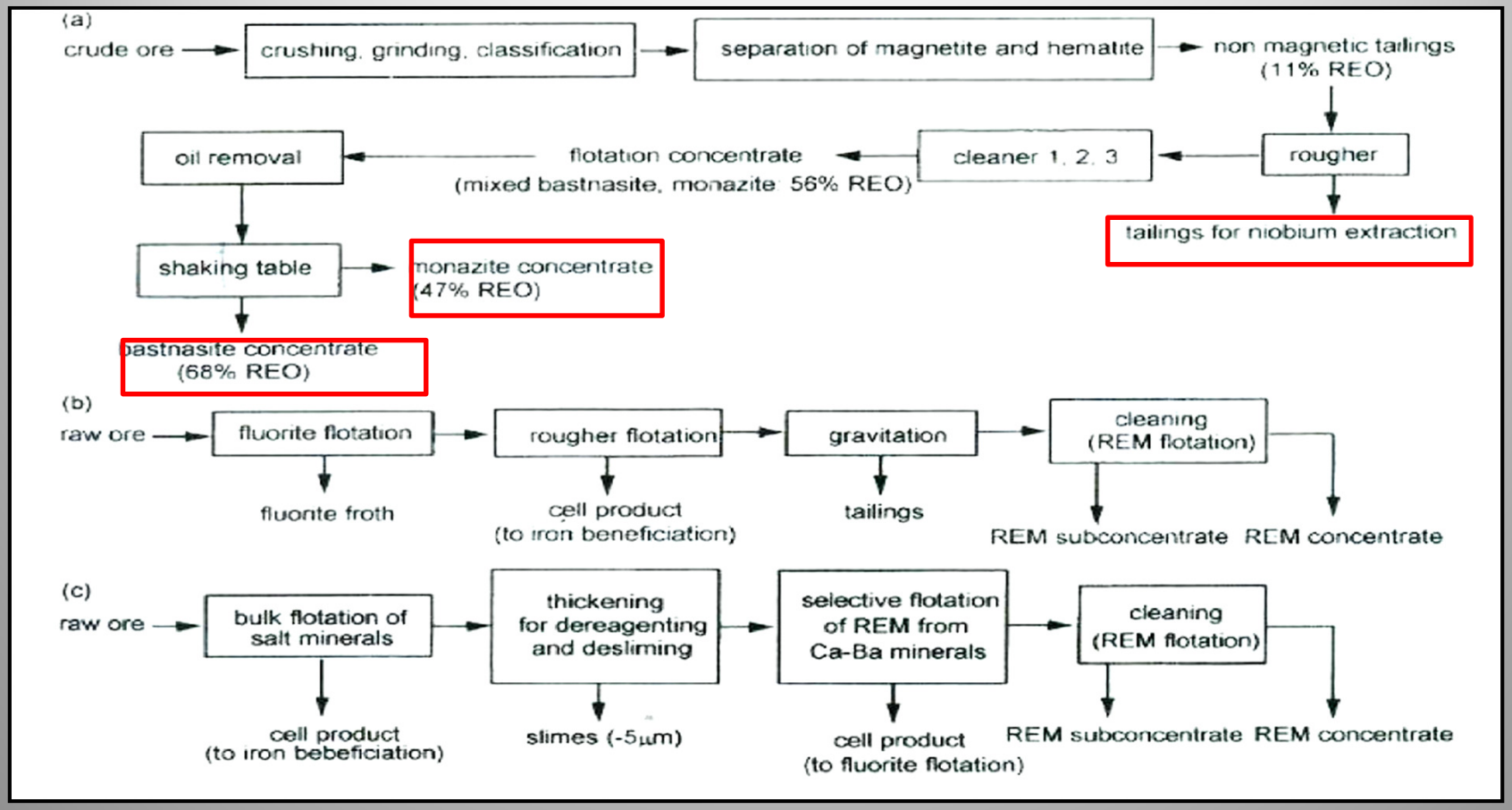
Rare Earths and Niobium are a By Product of Iron Ore Production

Mountain Pass & Bayan Obo TREO Ores

Primary TREO By Product TREO

Rare earth	Bastnasite, Mountain Pass, California, U.S.	Bastnasite, Bayan Obo, Nei Monggol, China
La	33.2000	23.0000
Ce	49.1000	50.0000
Pr	4.3400	6.2000
Nd	12.0000	18.5000
Sm	0.7890	0.8000
Eu	0.1180	0.2000
Gd	0.1660	0.7000
Tb	0.0159	0.1000
Dy	0.0312	0.1000
Ho	0.0051	trace
Er	0.0035	trace
Tm	0.0009	trace
Yb	0.0006	trace
Lu	0.0001	trace
Y	0.0913	0.5000

Bayan Obo Iron Ore Beneficiation For TREO and Niobium Production



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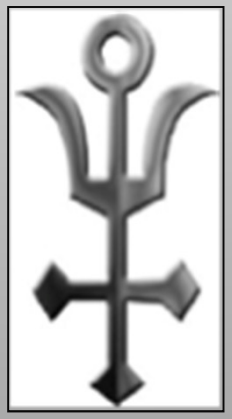
ANTIMONY
A US Critical Metals Program Success



Antimony History

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

Antimony Uses and Applications

- Sb_2O_3 for flame retardants, pigments, and polyethyeleneterephthalate catalysts.
- $NaSb(OH)_6$ for flame retardants and glass.
- Antimonial lead and alloys for batteries.
- Sb_2S_3 in brake liners and matches.
- Sb_2O_5 for flame retardants.

ANTIMONY

Antimony metal is used as an alloy hardener as well as in metallurgical applications.

Antimony metal is also the raw material of antimony oxide.

ANTIMONY

Antimony Trioxide is primarily used as a fire retardant in plastic insulations and fabrics as well as electronic devices and household appliances.

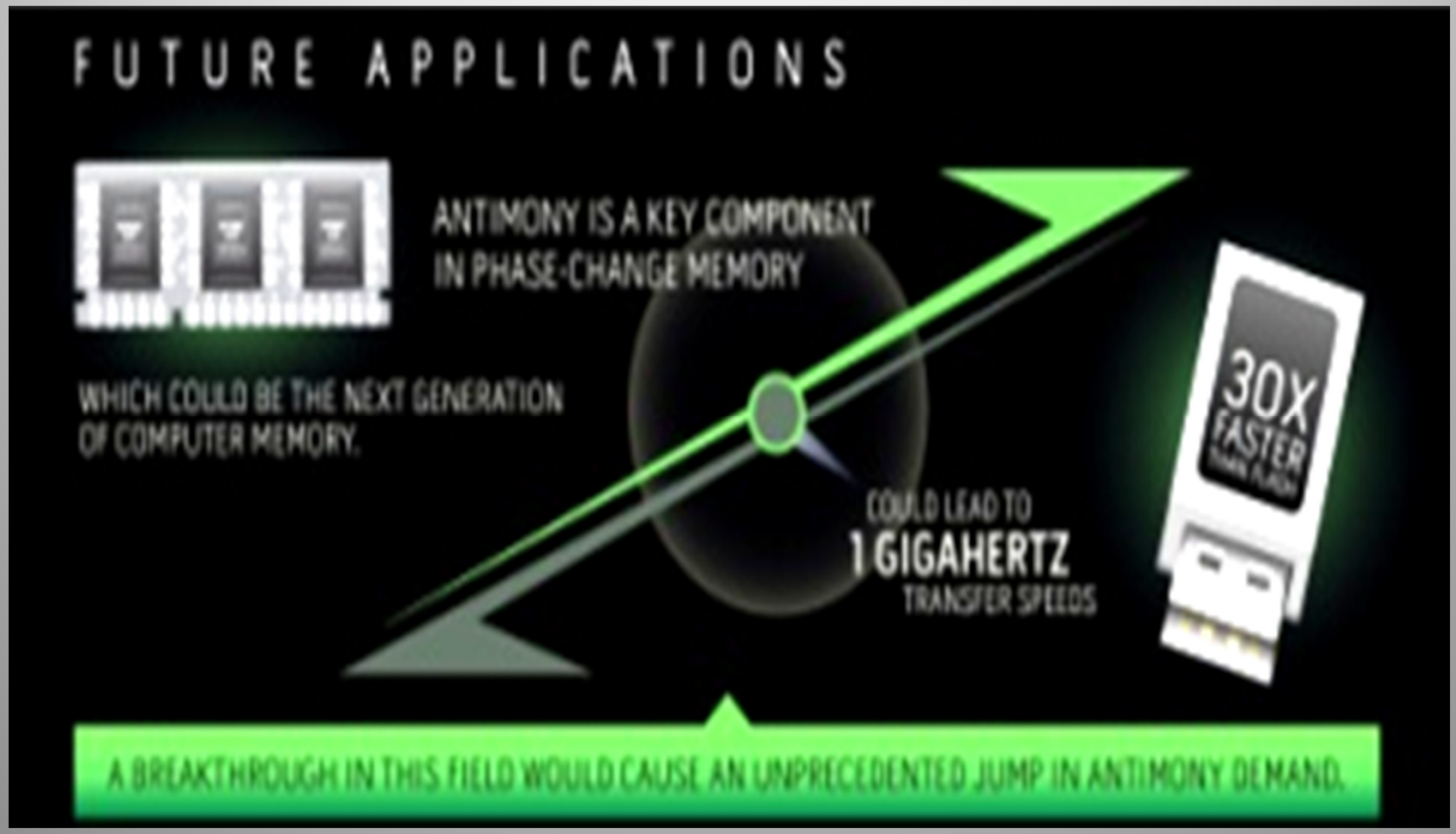
Sb_2O_3 can be used as a filling agent for various rubber, ceramic and fibre products and as a pigment in oil paints and as a catalytic agent in organic synthesis.

ANTIMONY

Antimony acetate is primarily used as catalyst for poly-condensation of polyester.

Antimony acetate improves the poly-condensation time, especially in continuous processes and significantly reduces impurity levels in PET resin.

ANTIMONY
Phase Change Computer Memory



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ANTIMONY

RENEWABLE ENERGY NOVEL SOLAR CELL

Scientists from the US Naval Research Laboratory (NRL) have proposed a novel triple-junction solar cell utilizing antimony with the potential to break the 50 per cent conversion efficiency barrier.

Antimony Occurrence and Mineralogy

- Abundance in earth's crust 0.2 g/t
- Antimony is a chalcophile and a metalloid
- Over 100 Antimony minerals are known
- Stibnite, Sb_2S_3, is the predominant mineral

COMMON ANTIMONY MINERALS

Horsfordite Cu_6Sb	Dyscrasite Ag_3Sb	Stibiodomeykite $Cu_3(As,Sb)$
Aurostibite $AuSb_2$	Breithauptite NiSb	Arite Ni(As,Sb)
Ullmannite NiSbS	Gudmundite FeSbS	Stibnite Sb_2S_3
Stibiobismuthine $(Bi,Sb)_4S_7$	Tetrahedrite $Cu_{12}Sb_4S_{13}$	Annivite $Cu_{12}(Sb,Bi,As)_4S_{13}$
Freibergite $(Cu,Ag)_{12}Sb_4S_{13}$	Bournonite $PbCuSbS_3$	Stephanite Ag_5SbS_4
Ramdohrite $Ag_2Pb_3Sb_3S_9$	Andorite $AgPbSb_3S_6$	Geocronite $Pb5(As,Sb)_{12}S_8$
Zinckenite $PbSb_2S_4$	Jamesonite, $Pb_4FeSb_6S_{14}$	Boulangerite $Pb_5Sb_4S_{11}$
Falkmanite $Pb_3Sb_2S_6$	Meneghihite $Pb_4Sb_2S_7$	Cylindrite $Pb_3Sn_4Sb_2S_{14}$
Franckeite $Pb_5Sn_3Sb_2S_{14}$	Livingstonite $HgSb_4S_7$	Berthierite $FeSb_2S_4$
Famatinite Cu_3SbS_4	Stibioluzonite $Cu_3(Sb,As)S_4$	Berthonite $Cu_7Pb_2Sb_5S_{13}$
Bolivianite $Ag_2Sb_{12}S_{19}$	Sulfo-antimonite $Ag_2Pb_7Sb_8S_{20}$	Kermisite Sb_2S_2O
Stibiotantalite $SbTaO_4$	Stibiocolumbite $SbNbO_4$	Senarmontite Sb_2O_3
Romeite $5CaO:3Sb_2O_5$	Stibiconite $Sb_2O_4:H_2O$	Stenhuggarite $CaFeSbAs_2O_7$
Cervantite Sb_2O_4	Stibio-tellurobismutite $B_{11}0SbTe_7$	Valentinite Sb_2O_3

ANTIMONY

Supply Risk

The British Geological Survey's Risk List 2011, a supply risk index for chemical elements which are of economic value, indicated antimony as the element ***with the highest risk of supply disruption***. The list is determined by a number of factors which might impact on supply. These include:

Scarcity
Production concentration
Reserve base distribution
Governance

In the 2011 Risk List, antimony was ranked in the highest category of supply risk, ***even higher than rare earth elements.***

ANTIMONY

British Geological Survey

Risk list 2012 — Current supply risk index for chemical elements or element groups which are of economic value

Element or element group	Symbol	Relative supply risk index	Leading producer	Top reserve holder
rare earth elements	REE	9.5	China	China
tungsten	W	9.5	China	China
antimony	Sb	9.0	China	China
bismuth	Bi	9.0	China	China
molybdenum	Mo	8.6	China	China
strontium	Sr	8.6	China	China
mercury	Hg	8.6	China	Mexico
barium	Ba	8.1	China	China
carbon (graphite)	C	8.1	China	China
beryllium	Be	8.1	USA	Unknown

ANTIMONY

Antimony Market Factors

Supply from China is declining due to the Chinese government;

- reducing the number of antimony miners

- smelters are declaring antimony as a strategic mental

- imposing antimony production quotas since 2009.

- reserves are being depleted

ANTIMONY
Recent Global Headlines

Production stops at Kyrgyzstan's Kadamdzhay antimony smelter due to lack of feedstock

Chinese antimony metal prices stabilize as smelters withhold sales

Chinese antimony prices seen stabilizing amid production cuts

Hsikwangshan Twinkling Star, the largest antimony producer in the world, has stopped production at its concentrator in 2016

China announces qualified antimony exporters for 2014

The End of High-Grade Antimony Reserves in China—The Real Low Down

ANTIMONY

Antimony Market Factors

In 2010, the USGS reported that two actions caused production reductions in China, the worlds leading antimony producer.

In March, the Government stated it would not approve any new projects for antimony before June 30, 2011.

Also in March, the Government shut down about 100 antimony smelters in Chinas dominant antimony-producing region, an action aimed at closing illegal mines and curbing pollution.

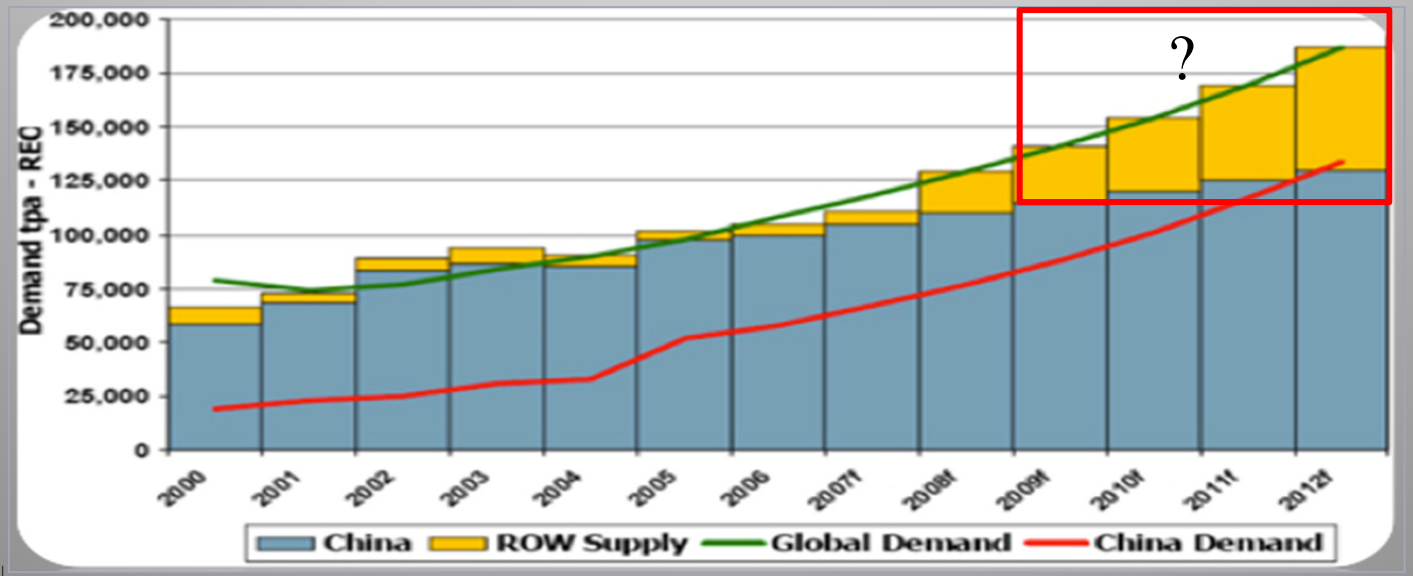
ANTIMONY

Antimony Market Factors

Global Demand is increasing as the:

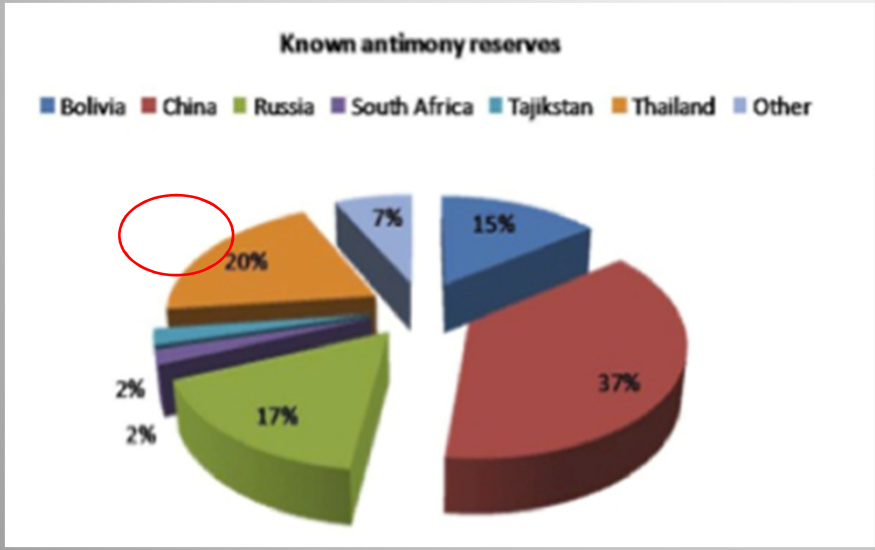
Chinese economy continues to grow at approximately 10% per year;

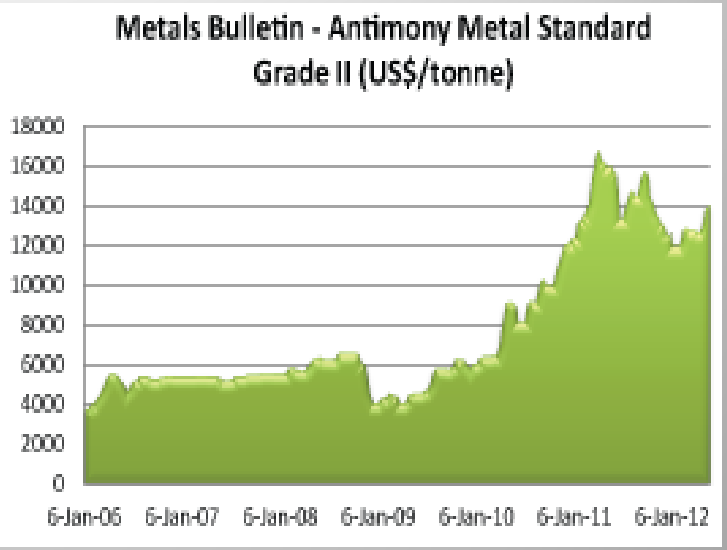
And the Western world is increasing the requirements on fire-proofing.



ANTIMONY

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





China has the majority of known metal reserves.
These are depleting rapidly.
Stibnite available for primary Sb production is a very scarce mineral.

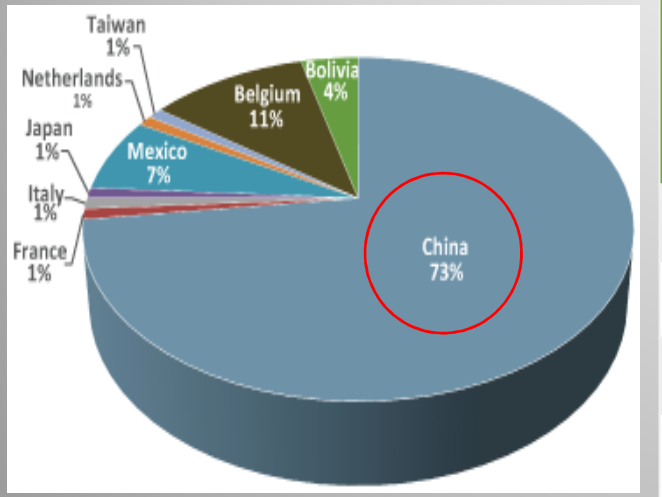
By Product Antimony is Often Viewed as a Smelter Penalty Metal

Penalty Element	Limit/ DMT[1]	Penalty Cost
Arsenic (As)	0.10%	$ 5.00/0.1 % (up to 0.5 % As) $ 11.00/ 0.1 % (>0.5 % As)
Bismuth (Bi)	200 ppm	$ 4.00/ 100 ppm (up to 1200 ppm Bi) $ 6.00/ 100 ppm (>1200 ppm Bi)
Selenium (Se)	0.05%	$ 5.00/0.01 % Se
Antimony (Sb)	0.10%	$ 4.00/0.1 % Sb
Cadmium (Cd)	200 ppm	$ 4.00/100 ppm Cd
Lead (Pb)	1%	$2.75/0.5 % Pb

1/ Dry Metric Tons

ANTIMONY

Sources of US Antimony in 2010

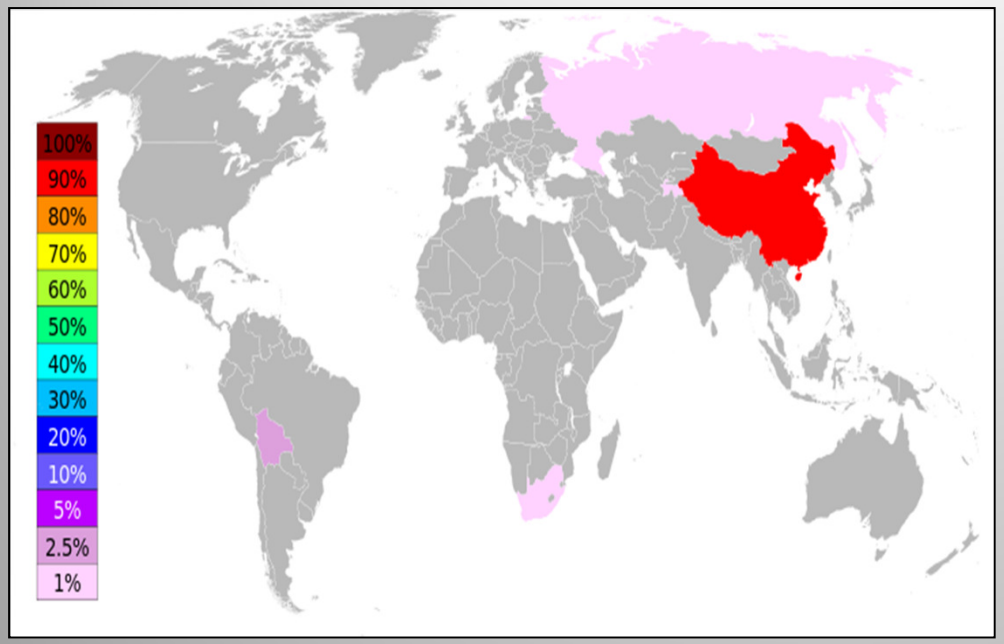


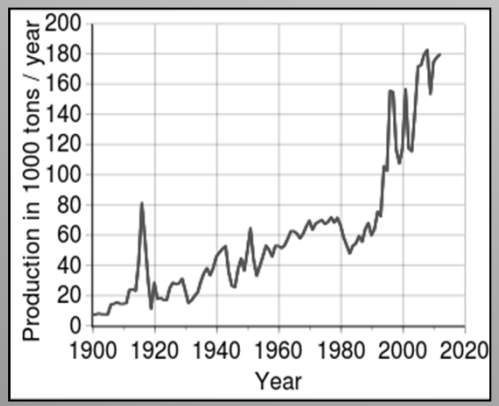
World Sources of Antimony

Country	Production (Metric Tons)	Percent	Reserves (Metric Tons)	Percent
China	150,000	89.8%	950,000	51.9%
Bolivia	4,980	3.0%	310,000	16.9%
Russia	3,000	1.8%	350,000	19.1%
South Africa	3,000	1.8%	21,000	1.1%
Tajikistan	2,000	1.2%	50,000	2.7%
Others	4,040	2.4%	150,000	8.2%
Total	167,020	100.0%	1,831,000	100.0%

Economics of Antimony

Chinese Dominate Production for Past 3 Decades



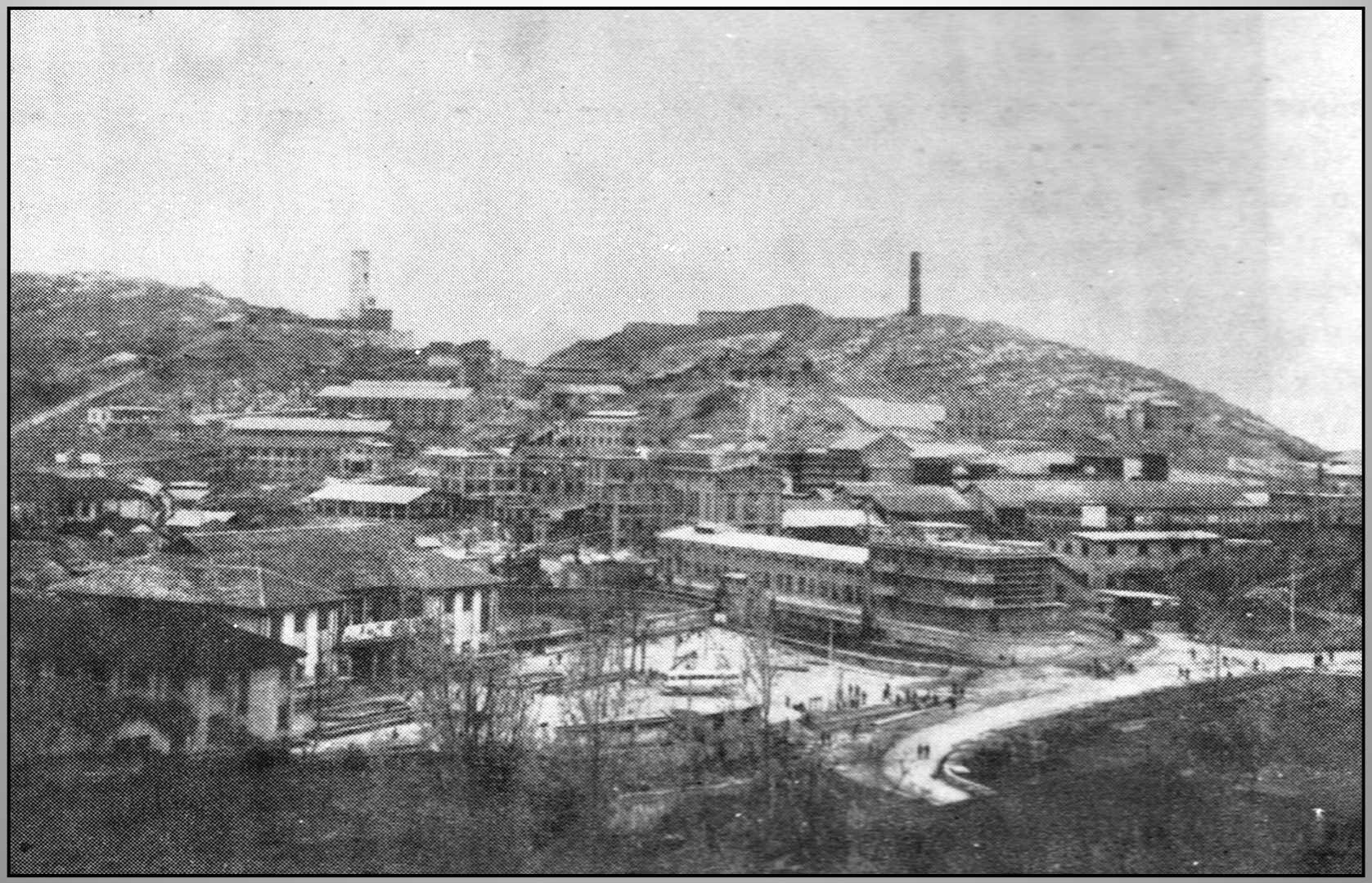


Country	Company	Capacity (tonnes per year)
Australia	Mandalay Resources	2,750
Bolivia	various	5,460
Canada	Beaver Brook	6,000
China	Hsikwangshan Twinkling Star	55,000
China	Hunan Chenzhou Mining	20,000
China	China Tin Group	20,000
China	Shenyang Huachang Antimony	15,000
Kazakhstan	Kazzinc	1,000
Kyrgyzstan	Kadamdzhai	500
Laos	SRS	500
Mexico	US Antimony	70
Myanmar	various	6,000
Russia	GeoProMining[42]	6,500
South Africa	Consolidated Murchison	6,000
Tajikistan	Unzob	5,500
Thailand	unknown	600
Turkey	Cengiz & Özdemir Antimuan Madenleri	2,400

Technology of Antimony

Professor Zhao Tian Cong

Hsikwangshan Antimony Complex



Hydrometallurgy of Antimony

- Hydrometallurgy is More Selective

  Than Pyrometallurgy And Is Viewed

  As More Environmentally Acceptable

- Hydrometallurgy Has Better Separations

  And Produces Higher Quality Sb Products

Hydrometallurgy of Antimony

- Alkaline Sulfide system
- Acidic Chloride system

Hydrometallurgy of Antimony

Acidic Chloride System

$$6FeCl_3 + Sb_2S_3 \rightarrow 2\,SbCl_3 + 6FeCl_2 + 3S^O$$

$$Sb_2S_3 + 6HCl \rightarrow 2SbCl_3 + 3H_2S$$

Plants were built in Australia and Canada

US Critical Metals Program 1942

Sunshine Mine
350 Million Troy Ounces of Silver From Tetrahedrite

Hydrometallurgy of Antimony

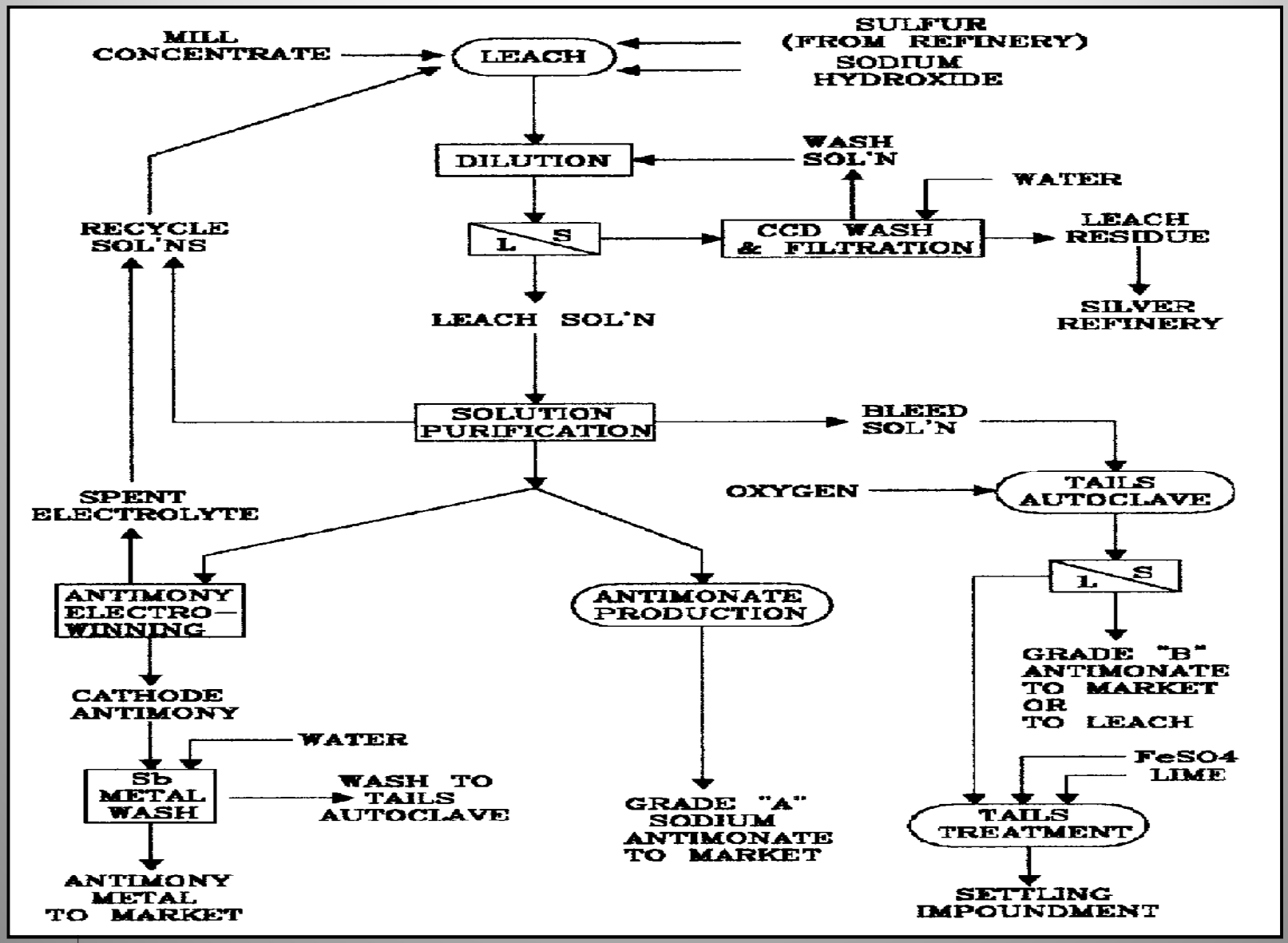
Alkaline Sulfide System

$$Na_2S + Sb_2S_3 \rightarrow 2NaSbS_2$$

$$NaSbS_2 + Na_2S \rightarrow Na_3SbS_3$$

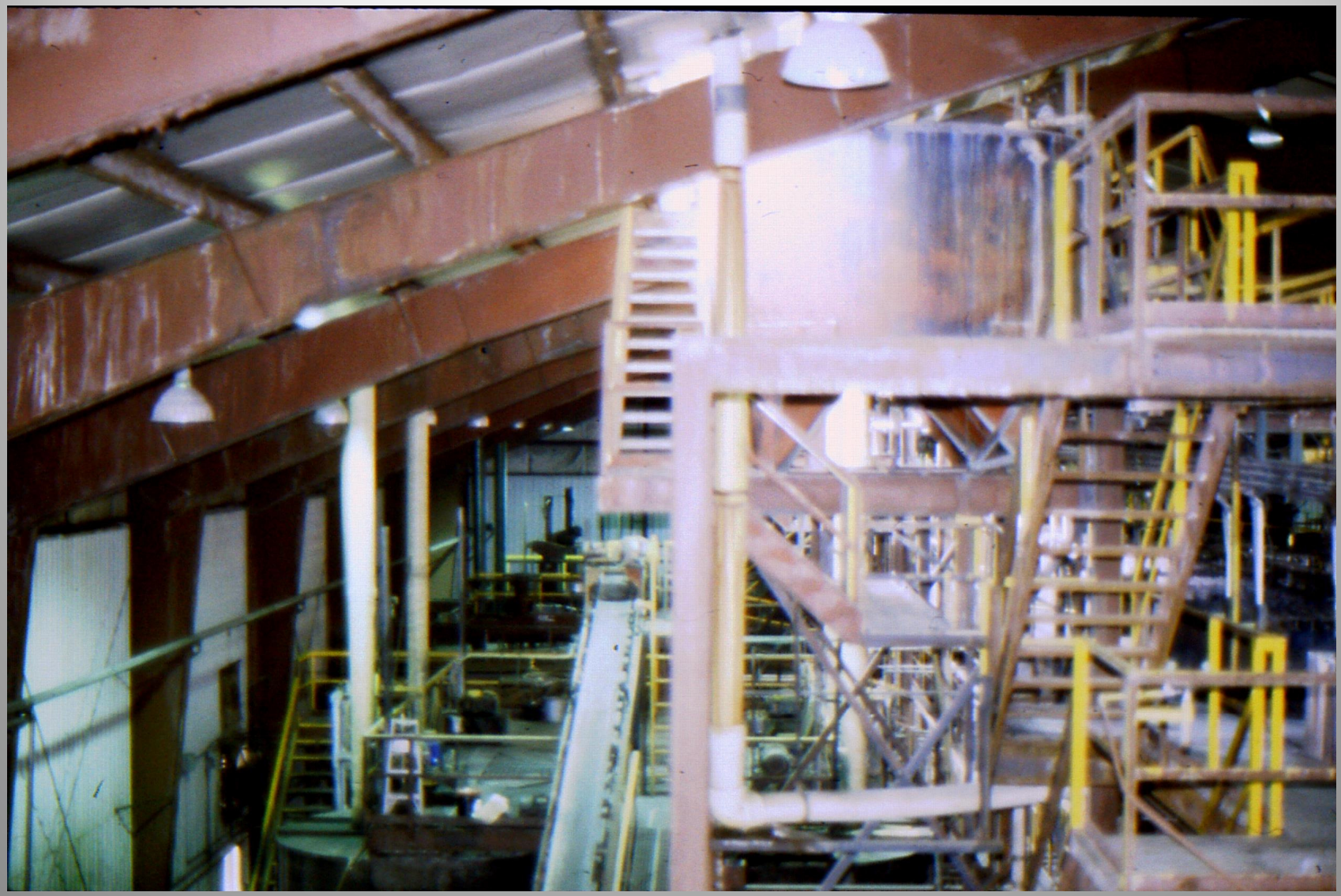
Sunshine Mine industrial Sb plant operated successfully for 60 years.
Built in 1942 as part of US Critical Metals Program during WWII.
High purity metal, sodium antimonate and antimony oxide were produced.

Sunshine Mining Hydrometallurgical Antimony Process



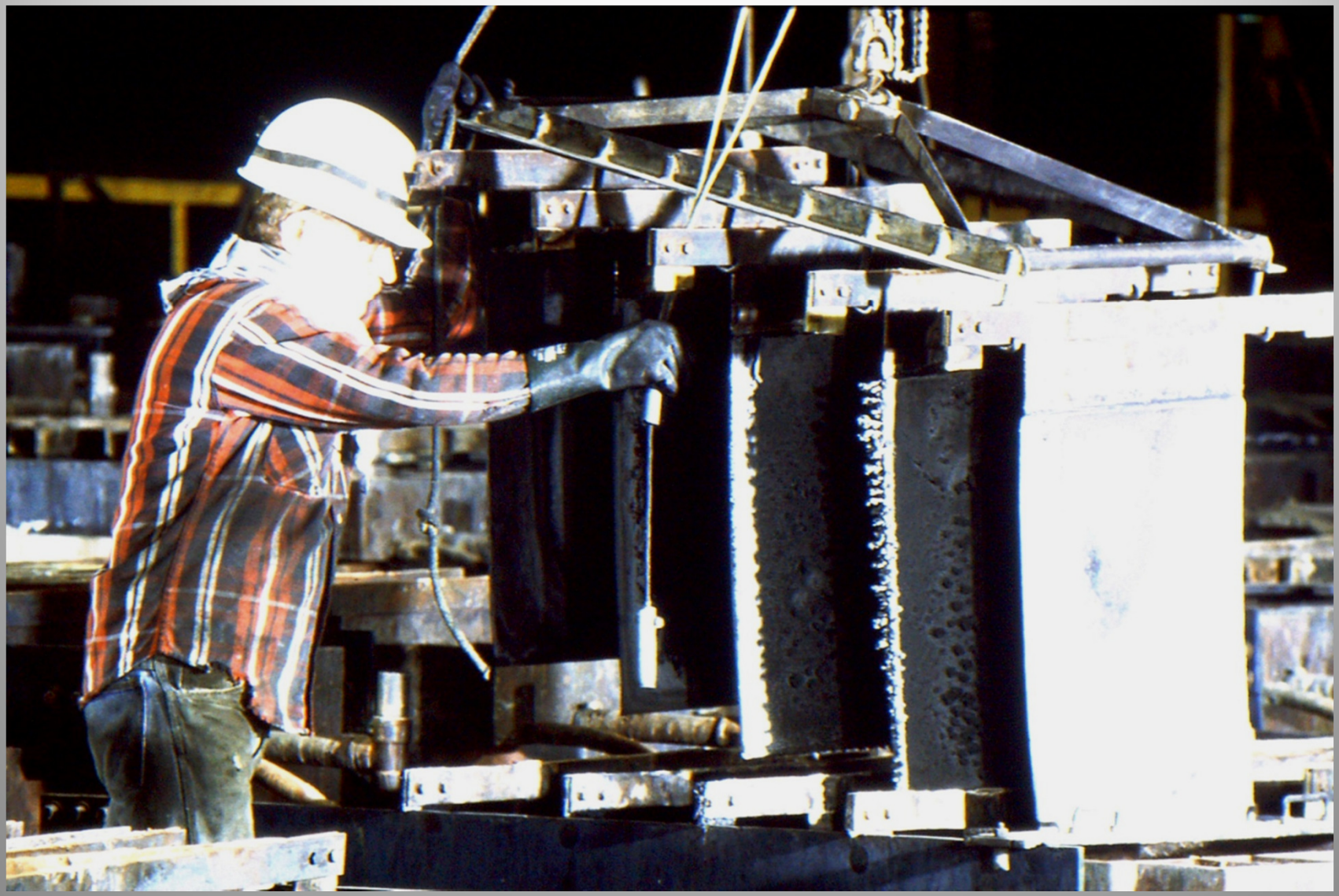
Sunshine Hydrometallurgical Antimony Plant

Sunshine Hydrometallurgical Antimony Plant



Sunshine Hydrometallurgical Antimony Plant

Sunshine Hydrometallurgical Antimony Plant



SUMMARY

- By Product Metals Production is Common.
- Some Critical Metals Primary Mineral Resources are Depleted and Truly Rare.
- Smelter Penalty Metals Can Be Produced as Value Added By Products.
- US Critical Metals Programs Have Previously Implemented Effective By Product Production.

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