   

Extraction of rare earth elements from acid mine drainage precipitates

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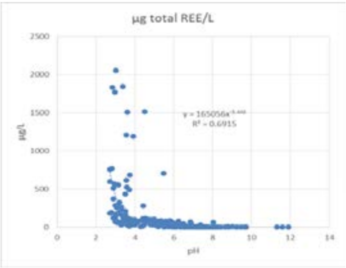
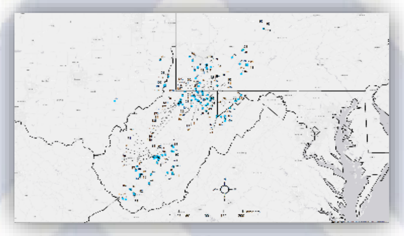
Presentation Outline

1 REEs in AMD



2 Resource Characterization



3 Process Design/Test

4 Summary and Questions

Classification

Rare Earth Elements

Light | Heavy

Critical

*Unstable

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	**Y**	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	**Nd**	Pm*	Sm	**Eu**	Gd	**Tb**	**Dy**	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pt	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Our REE Projects

DE-FE0026927

- Phase 1 ETD30 Completed
  - Development of a cost-effective & environmentally benign process to treat and recover REEs from AMD
  - Perform a preliminary process system Design and Techno-Economic Analysis
- Phase 2 ETD50
  - Build and operate a bench-scale pilot plant
  - Update cost and performance metrics
  - Supply chain/commercialization plan
  - Target product grade = 2% REE

DE-FE0026444 ETD39 Completed

- Conduct a broad sampling campaign (> 150 sites).
- Perform a detailed assessment at promising sites
- Report REE concentrations and elemental distributions

DE-FE0031524 ETD53

- Develop a novel process for capturing REEs upstream of AMD treatment
- Synthesize with a downstream process to produce high-grade REE products, >90% REO

Definitions:

- Basket Price
  - Weighted value
    - market price of each REE oxide x concentration/total REE concentration
  - Assumed market price of a kilogram of mixed rare earth oxide

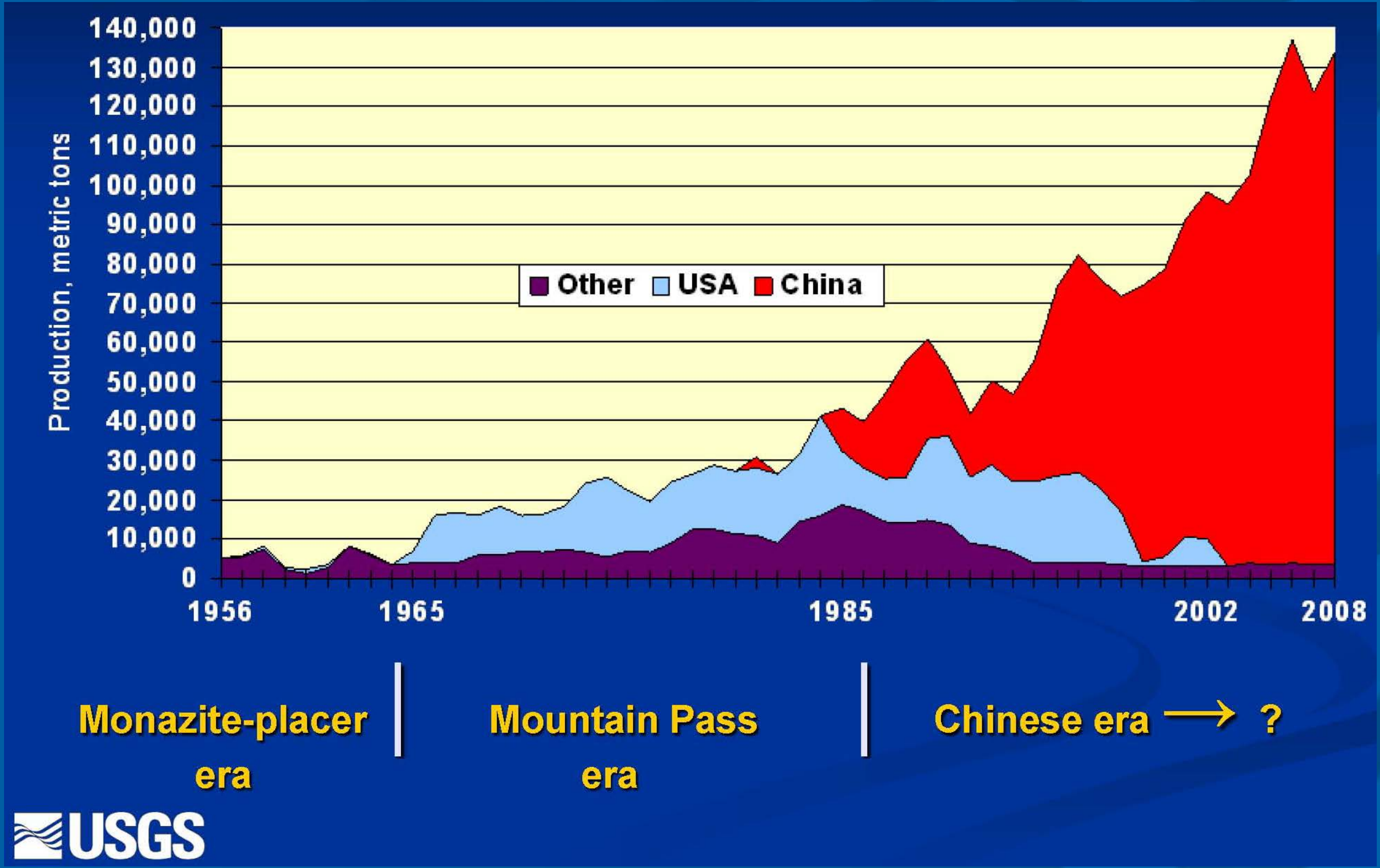
- Contained Value
  - Basket price x mass of dry sludge = $/ton of dry sludge

MOLYCORP REE MINE, MOUNTAIN PASS CA

Drivers:

- The U.S. imports nearly all of its REEs
- Mostly from China
- One operating US mine (maybe)
- USDOE seeks additional domestic sources from fossil energy sources
- Minimal environmental footprint
- Move quickly to market

Our strategic disadvantage: China controls exports ~ 35kt/yr



Projected TREE demand through 2025 (tons/year)

	Global demand @ 7% ann. Growth	USA demand total*	USA demand defense**
2017	158,403	15,840	792
2018	169,845	16,984	849
2019	182,176	18,218	911
2020	195,469	19,547	977
2021	209,804	20,980	1,049
2022	225,265	22,527	1,126
2023	241,947	24,195	1,210
2024	259,951	25,995	1,300
2025	279,387	27,939	1,397

??

* 10% global

** 5% USA demand

This assumes that USA manufacturing demand does not increase beyond current rates

RARE EARTH ELEMENTS IN AMD SLUDGE

Global demand/supply

REE as oxide	2015 demand tons/year	2015 supply tons/year
total REE	180,000	208,500
cerium	65,500	82,500
neodymium	37,500	32,500
europium	750	600
terbium	475	400
dysprosium	2,750	1,800

Many deposits have high concentrations but low recoverability: The granite counter top argument

Current and Proposed REE Developments

Conc.	mg/kg	basis	location
0.0300%	300	total REE	south China
0.0160%	160	Dysprosium	Kipwa, Canada
0.5800%	5,800	total REE (low)	Dotson Dike, Alaska
1.0540%	10,540	total REE (high)	Dotson Dike, Alaska

USDOE/NETL Project objectives

- Feedstock TREE > 300 mg/kg
  - Characterize and quantify
- Concentrate TREE > 2%
  - Small scale demonstration
- Prove significant supply to the domestic market

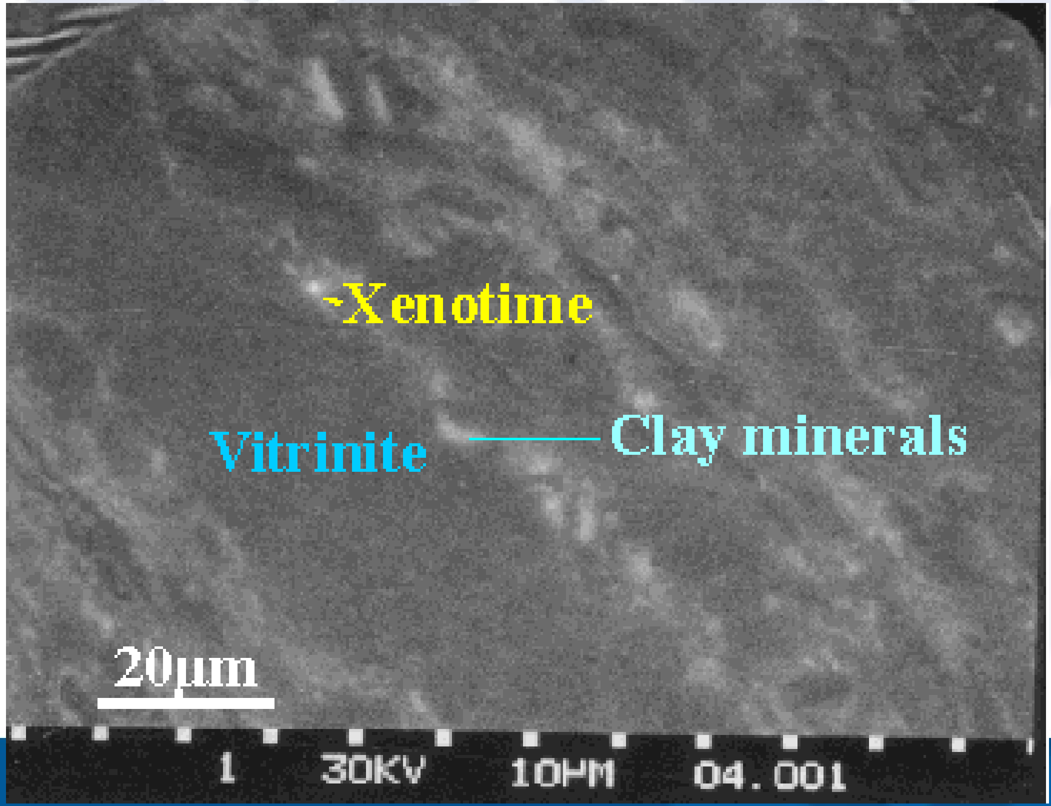
Conventional REE Ores

- Bastnasite (carbonate) or monzonite (phosphate)
  - both generally in igneous complexes
- Extraction requires severe comminution, acid dissolution to liberate REE from Al-Si matrix
- Refining via solvent extraction/electro-winning
- Contains uranium and thorium….So the tailings are acidic and radioactive
- Chinese deposits include iron ore and laterites

Mineral associations in WV coals

from WVGES

- Monazite (less commonly xenotime): REE (PO_4 SiO_4) weathered from granite as micron-sized particles
- Does not dissolve in weak acid, requires concentrated acid to liberate REEs
- When burned in a PC boiler nearly all of the inert minerals fuse into alumino-silicate glass
- Which is even more Resistant to acid attack

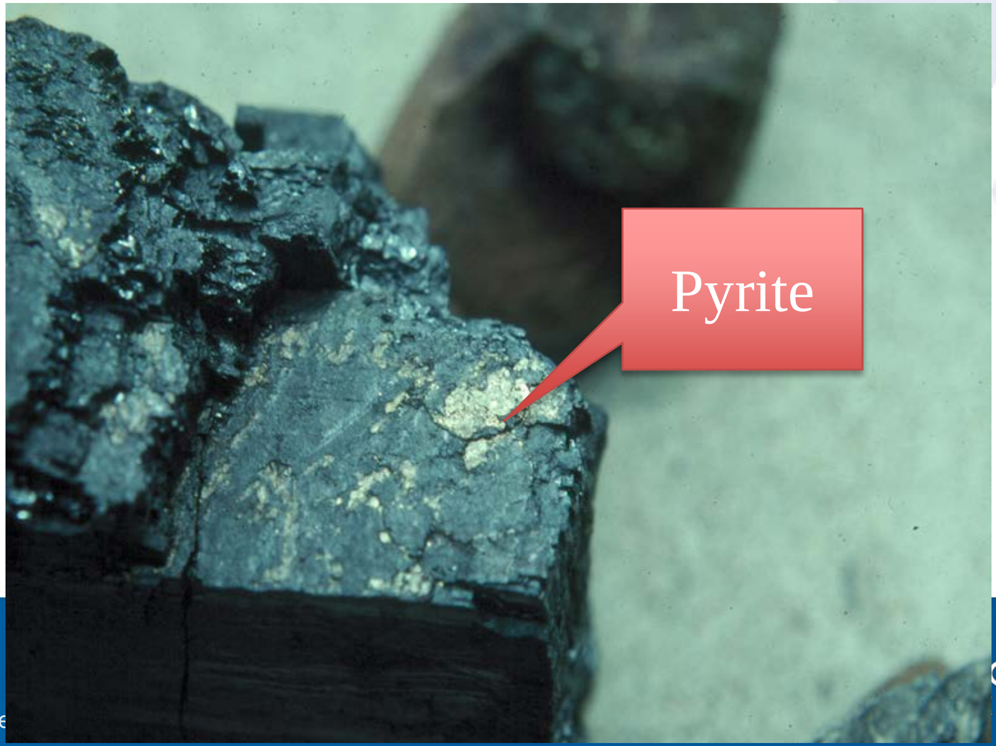


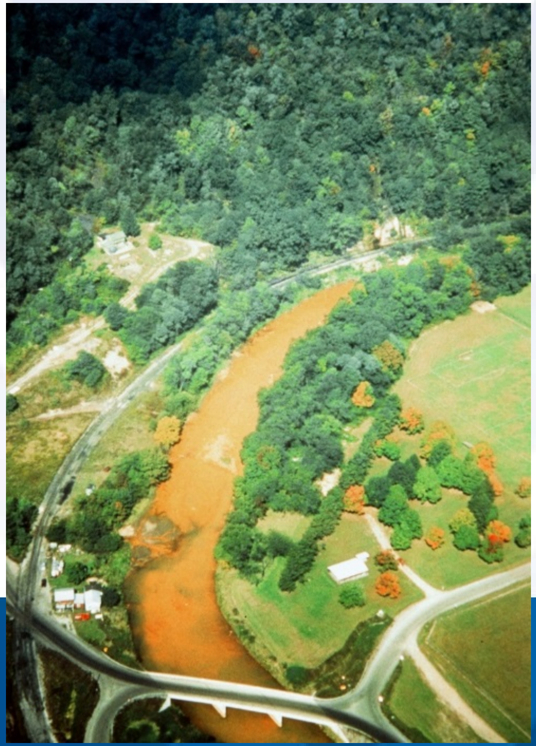
Acid Mine Drainage Chemistry

1. H_2SO_4 leaches REEs from shale
2. REE's precipitate with $Fe(OH)_3$

Pyrite + O_2 + H_2O
= Fe^{2+} + H_2SO_4

Fe^{2+} + O_2 + OH^-
= $Fe(OH)_3$



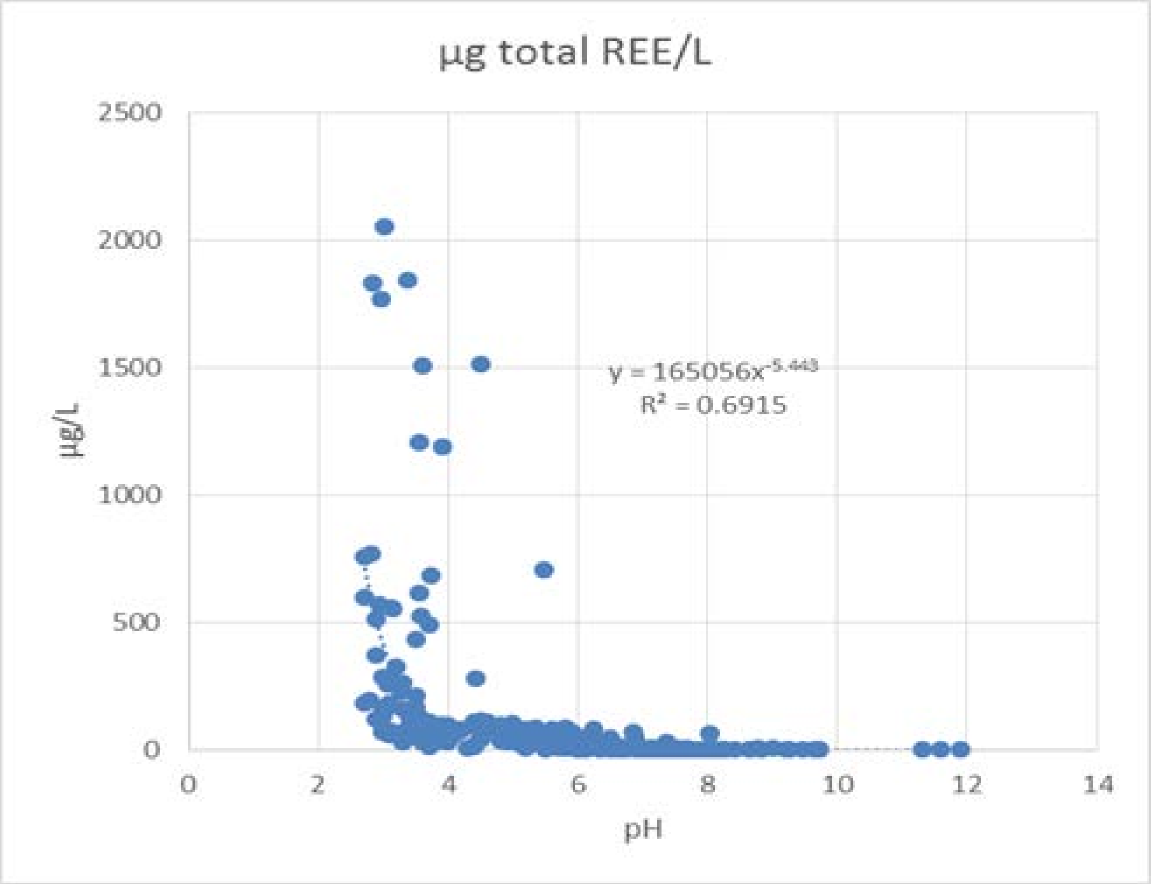


Typical, large AMD treatment plant

Lime tower left, clarifier center

Mixers, aerators

REE concentration in AMD is a function of raw water pH

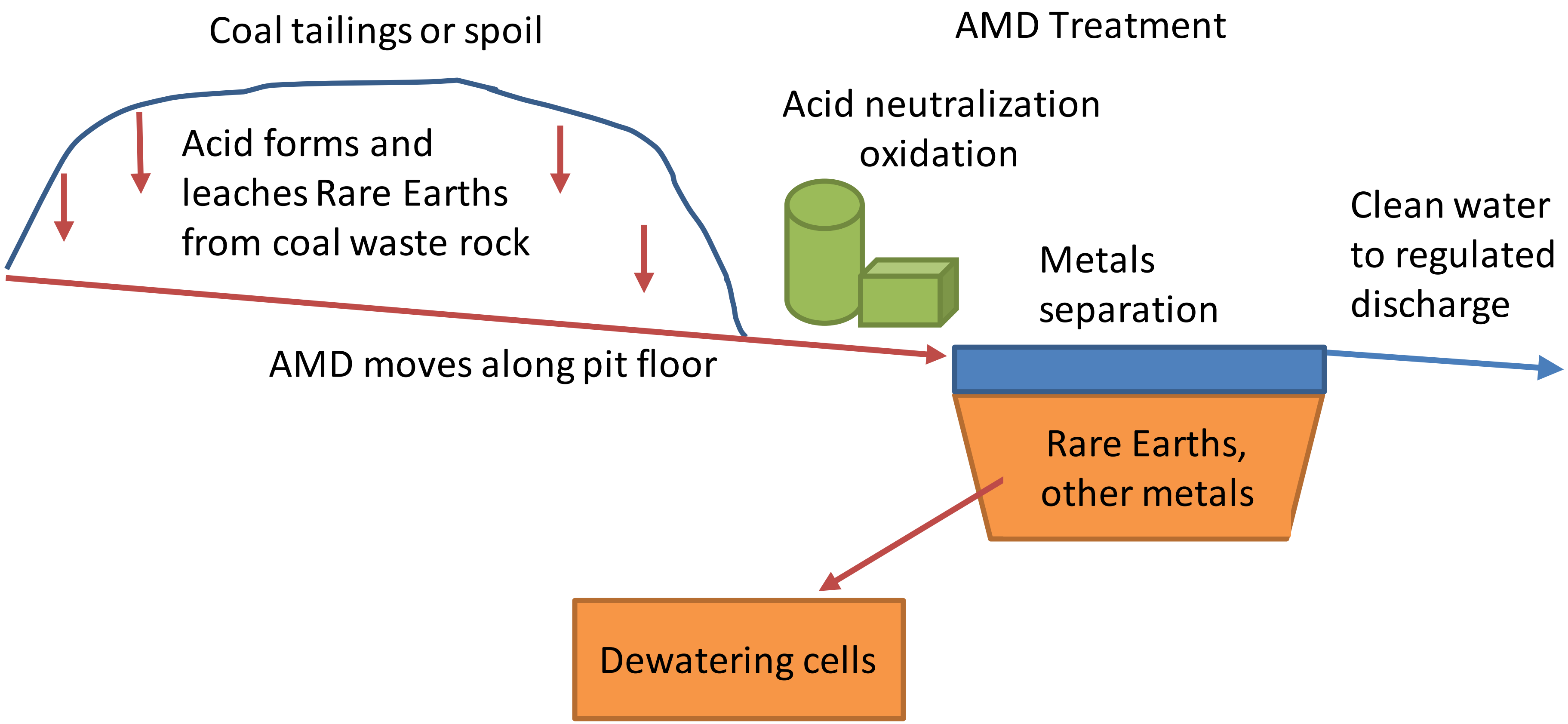


Solubility perfectly mirrors Fe^{3+}

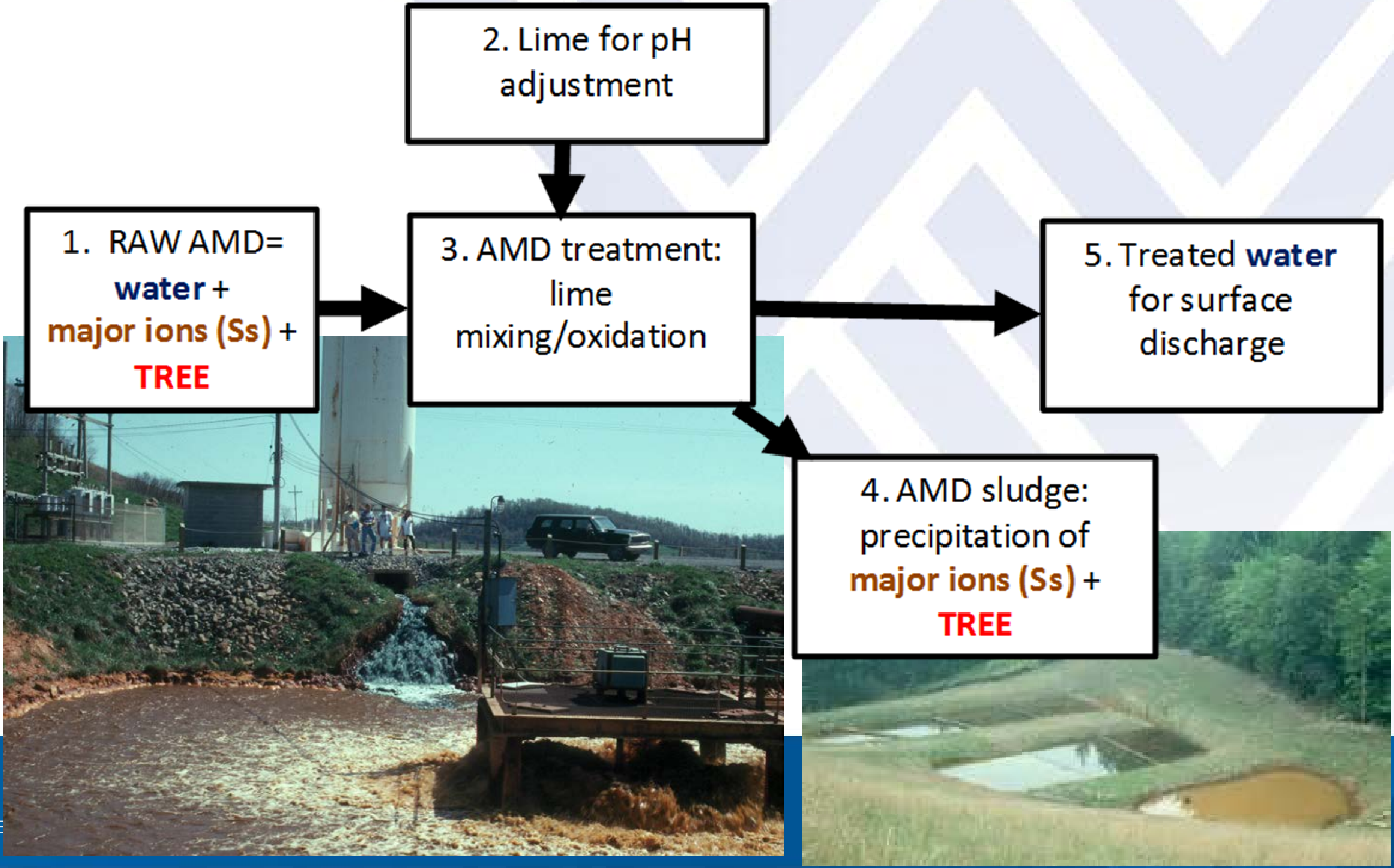
AMD Sludge: $Fe(OH)_3$ and anything else that precipitates as a hydroxide

The

Acid Mine Drainage (AMD) Treatment Typical layout

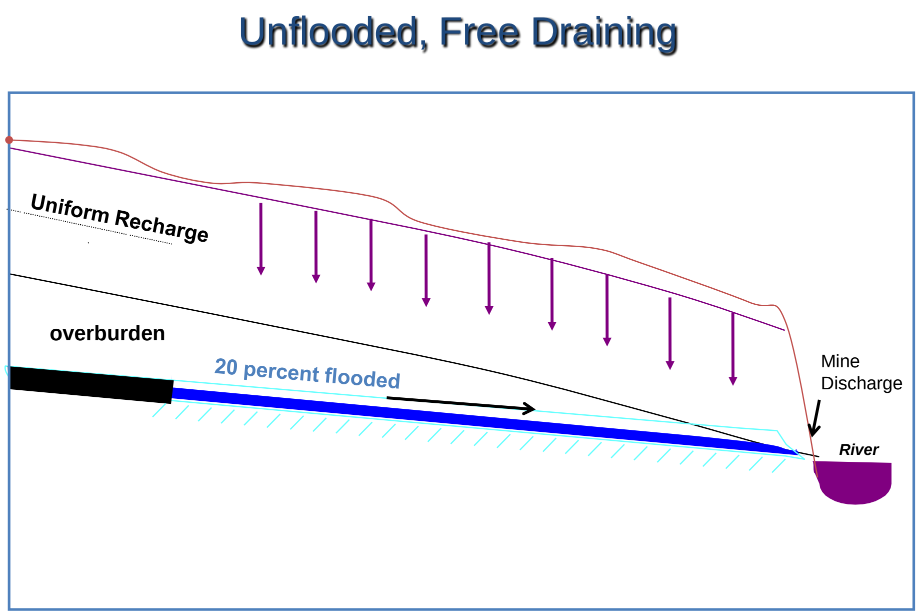


Conventional AMD Treatment

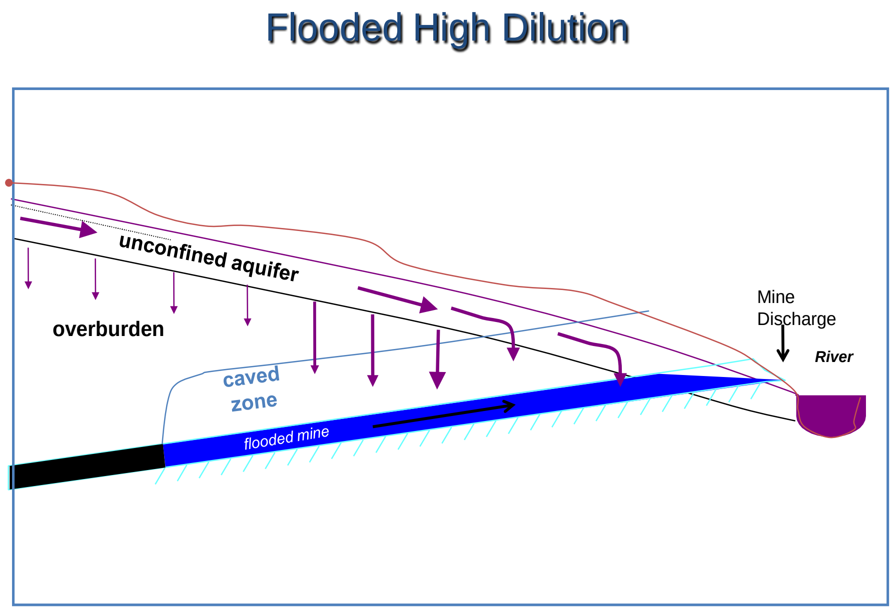


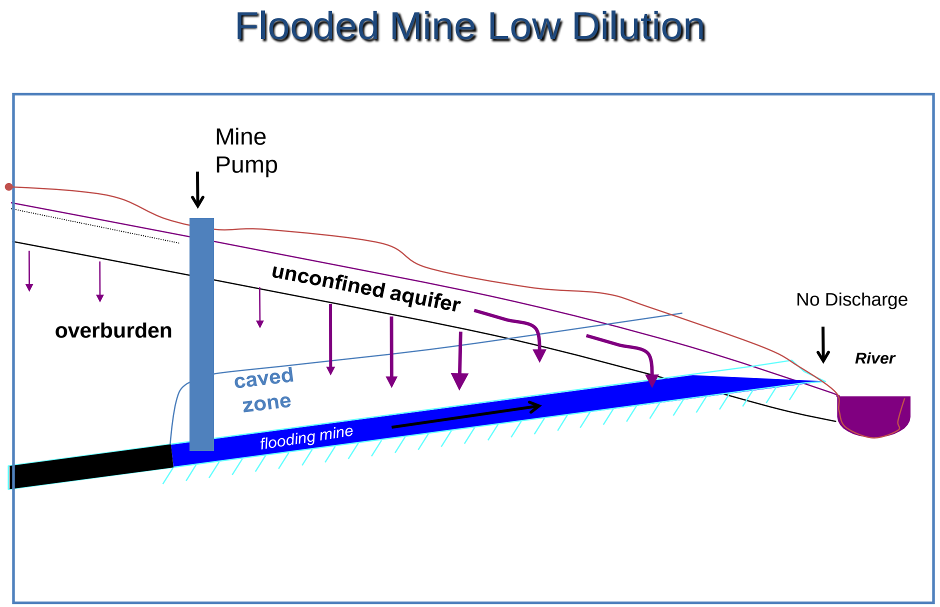
In deep mines the extraction point will control REE concentration

Low pH/high REE



High pH, low REE





Resource characterization, Valuation

Metal value: $555/kg each REE Processed to pure metal

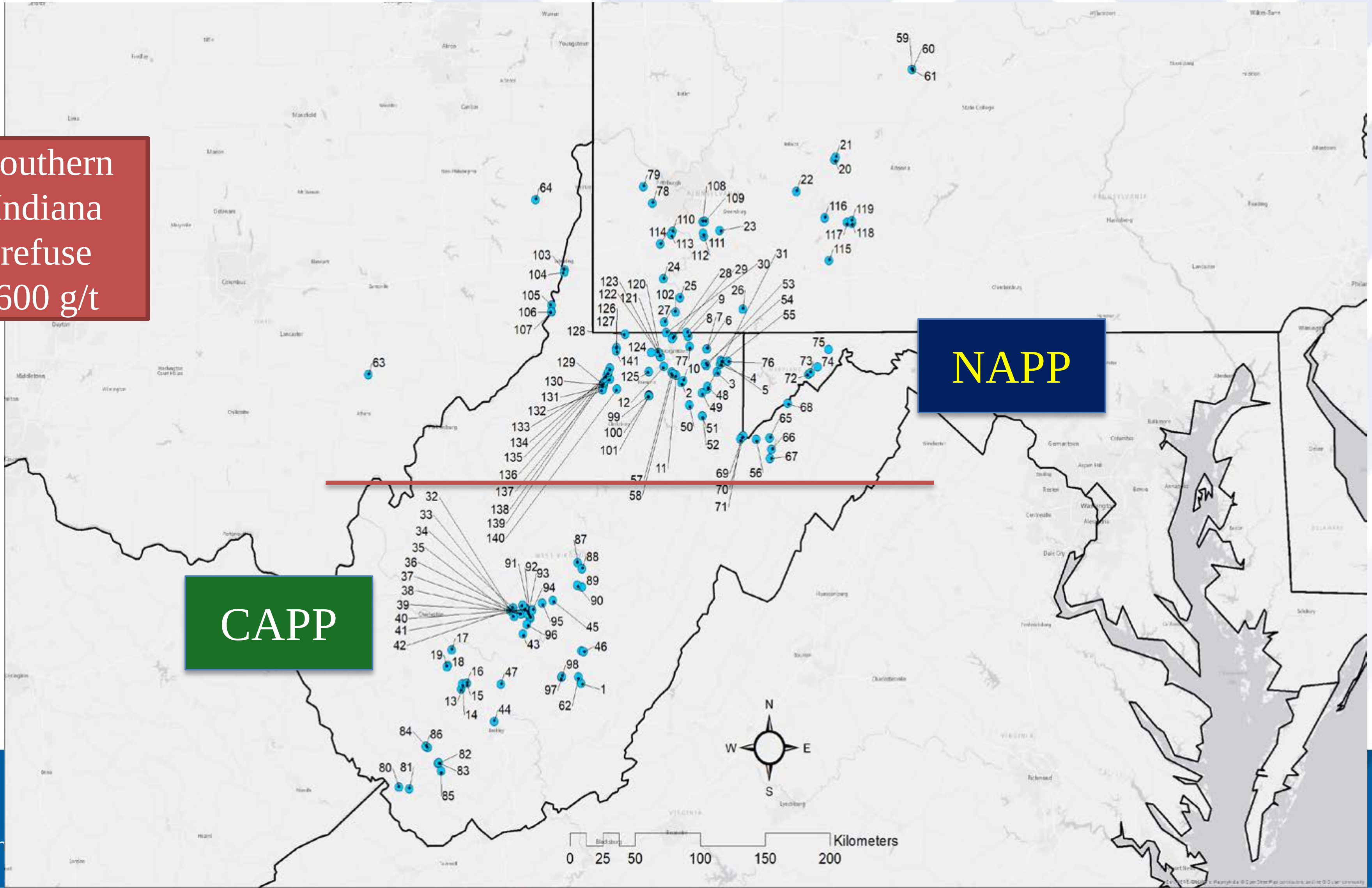
Oxide value:

Basket price: $237.23/kg TREE
weighted value

Contained value: $129.16/t dry sludge
accounts for handling and processing

140 Sampled locations: MD, OH, PA, WV

Southern Indiana refuse 600 g/t



Central vs. Northern Appalachian coal basins

Little difference between REE distribution or total concentration (g/t)

A sample from the Illinois Basin was similar to typical, low pH Appalachian AMD

Sites sampled:

CAPP	42
NAPP	110

	CAPP	NAPP	All
La	41.4	38.4	39.9
Ce	97.1	95.0	96.0
Pr	14.4	14.0	14.2
Nd	66.5	64.5	65.5
Sm	18.2	17.6	17.9
Eu	4.4	4.5	4.4
Sc	12.8	14.9	13.8
Y	88.6	108.7	98.7
Gd	23.9	24.3	24.1
Tb	3.4	3.7	3.6
Dy	18.8	20.7	19.8
Ho	3.5	4.0	3.8
Er	9.1	10.7	9.9
Tm	1.0	1.4	1.2
Yb	6.7	8.1	7.4
Lu	0.9	1.2	1.0
TREE	410.6	431.6	421.1

LREE

Critical

HREE

AMD treatment concentrates REE in sludge to about 700 g/t

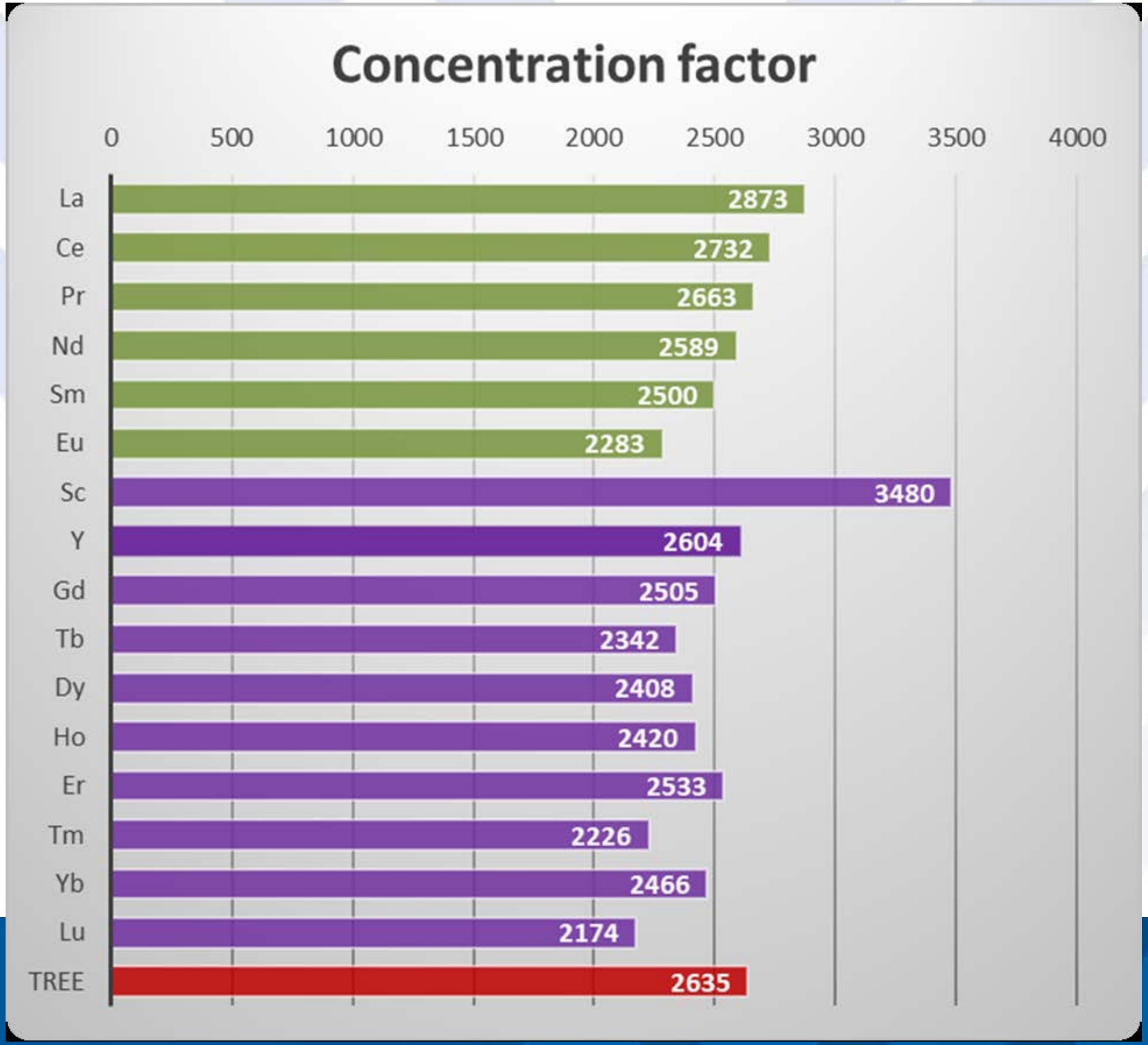
REE in NAPP vs. CAPP whole coal. Physical separation can increase REE concentrations to about 500-600 g/t

Pittsburgh Seam	
mg TREE/kg	
max	146.3
mean	34.6
min	7.3
st. dev.	22.0

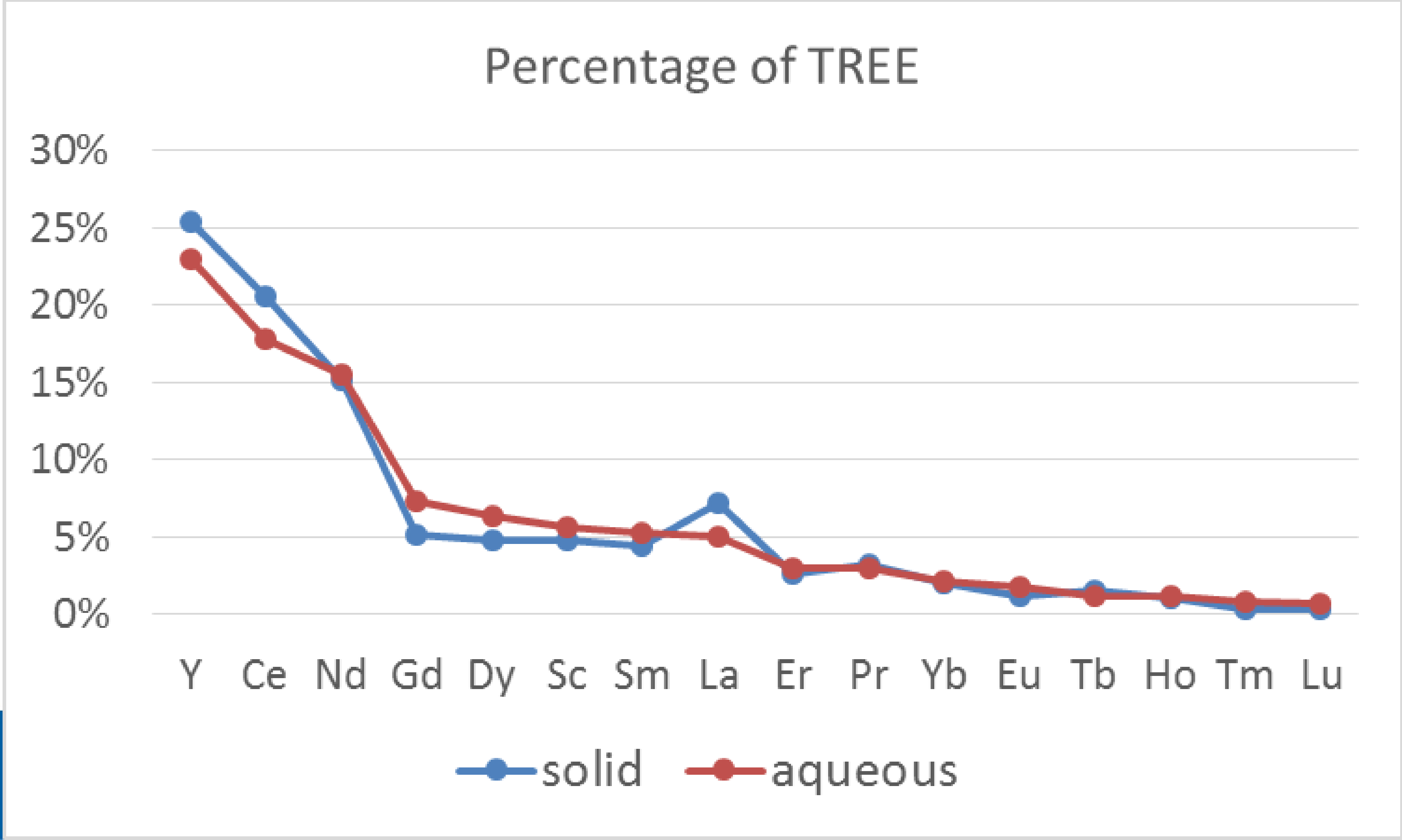
NAPP

Eagle Seam	
mg TREE/kg	
max	225.7
mean	49.5
min	9.3
st. dev.	42.2

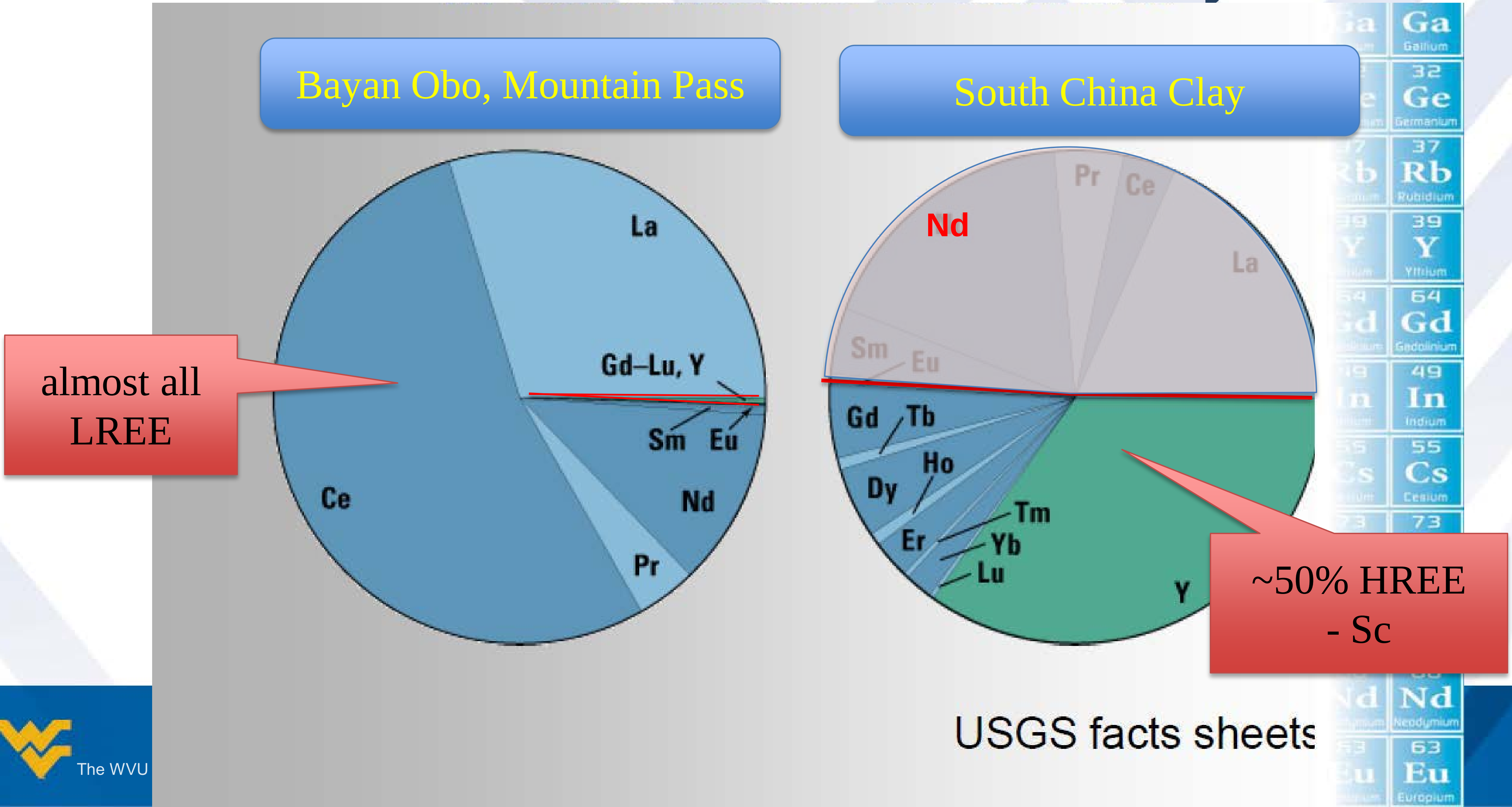
CAPP



All REEs precipitate to AMDp with nearly equal enthusiasm



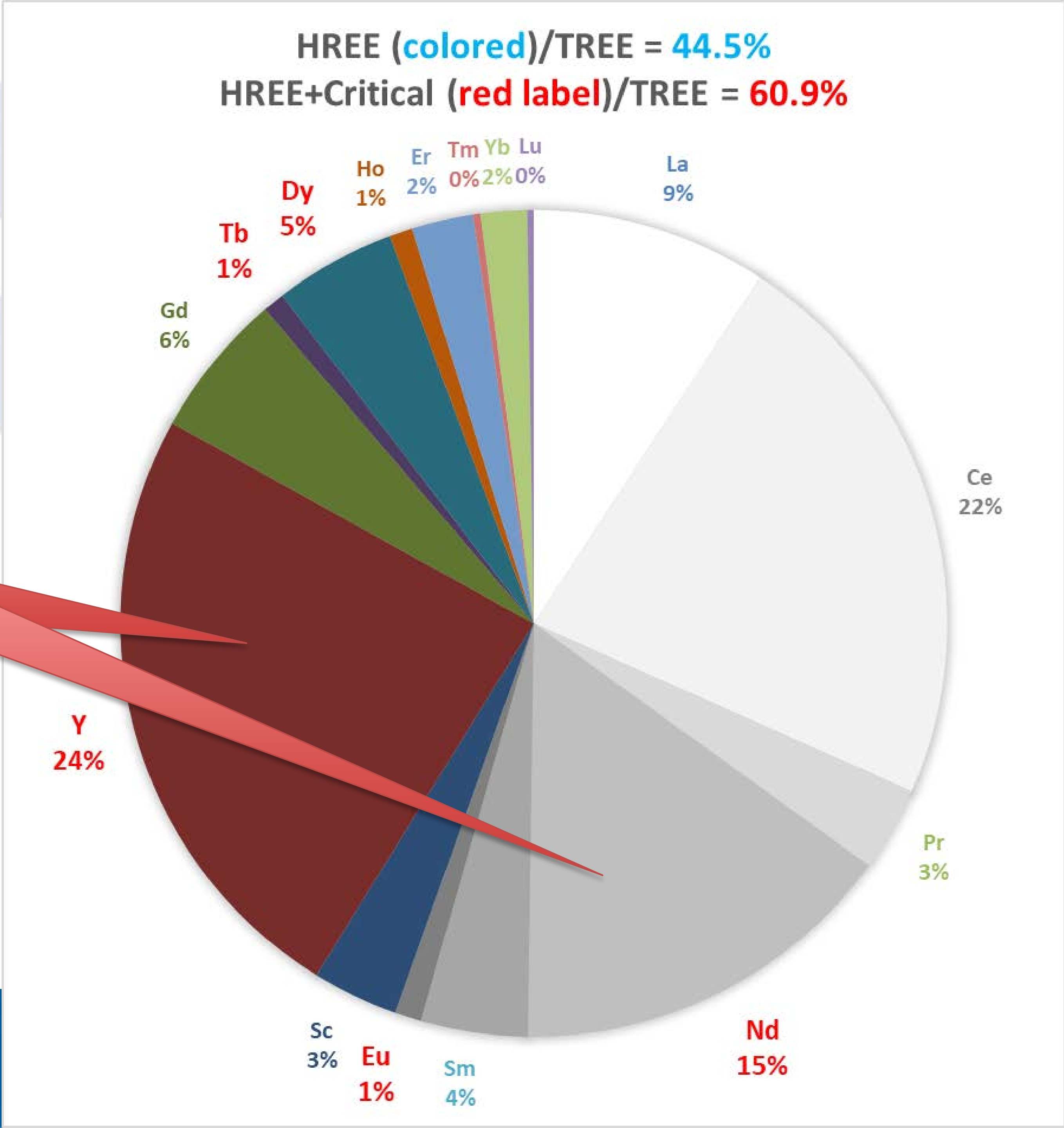
Distribution of HREE in AMD sludge is similar to south China clays



Heavy and Critical REEs in Acid Mine Drainage

n=155

High Y, Nd, both used in Nd: YAG lasers



Cobalt is present in all samples.
TREE x 0.75 = Co

REEE concentrations and weighted in situ value Scandium represents 82% of contained value.

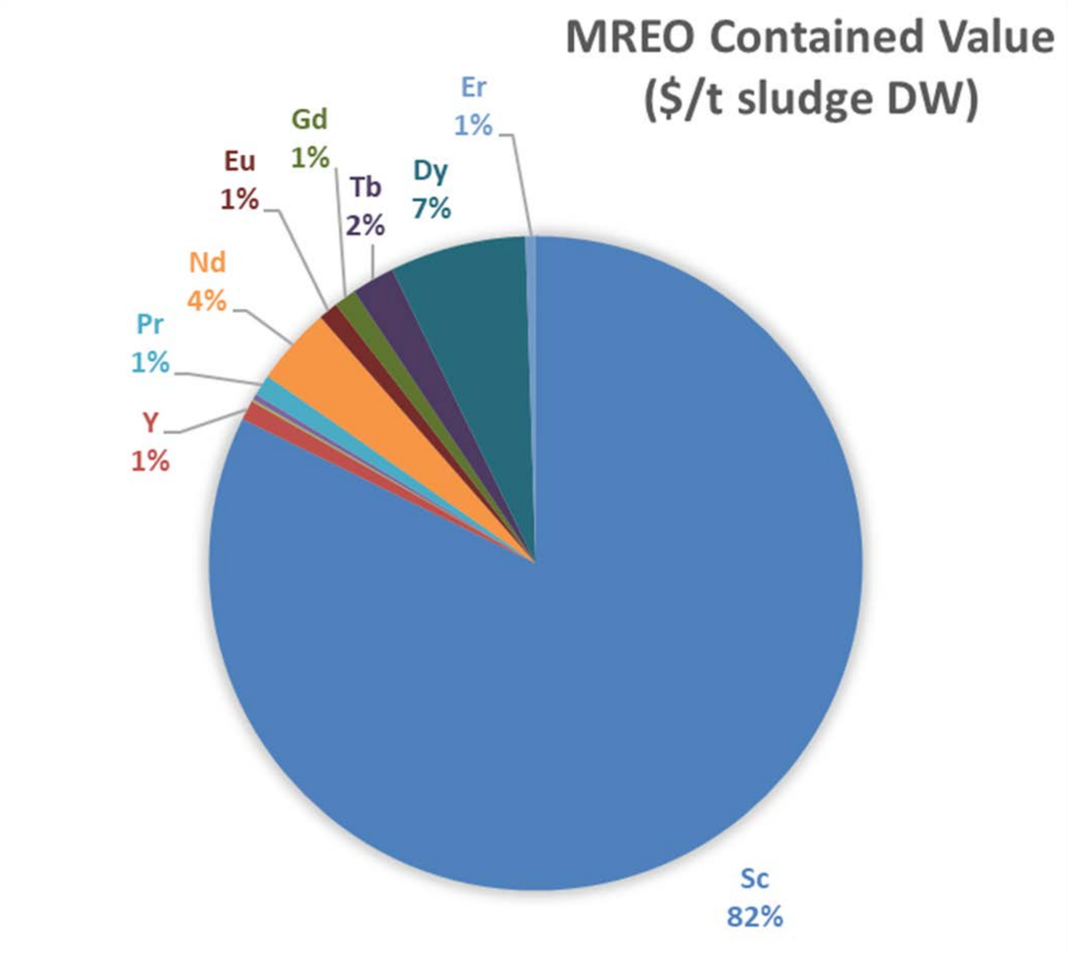
LREE

Critical

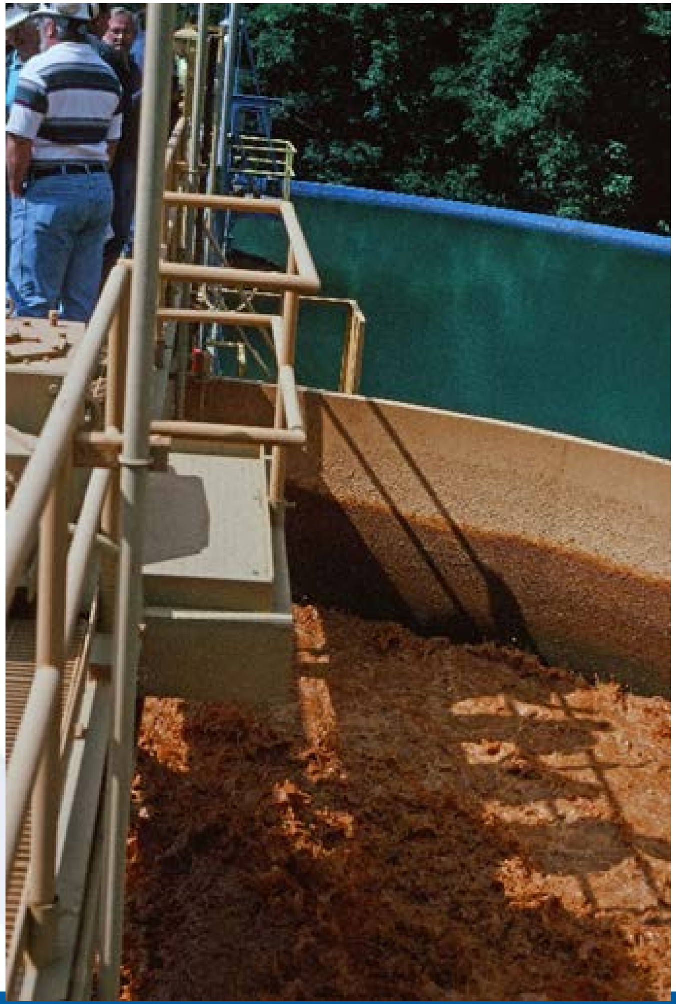
HREE

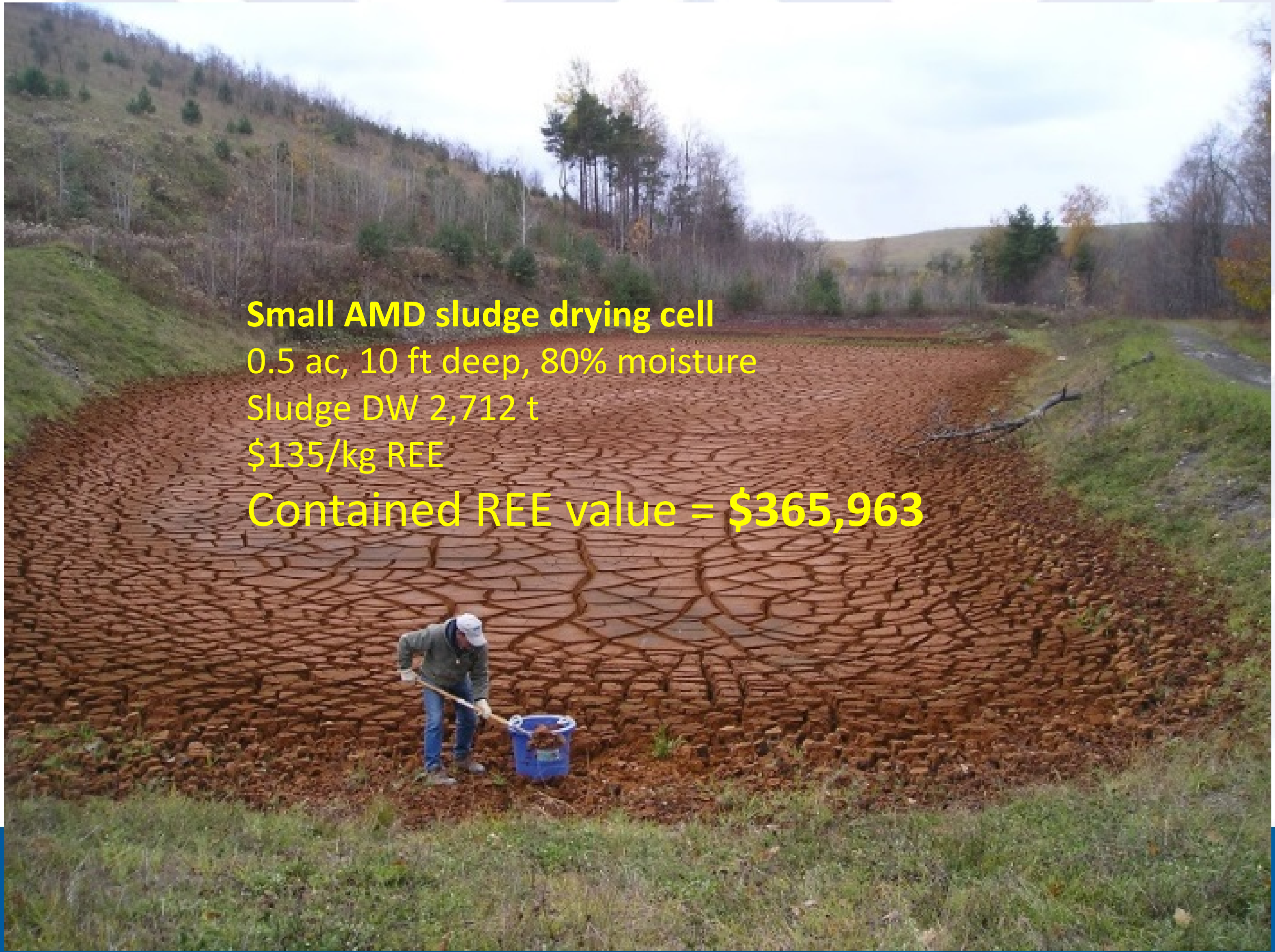
	TREE g/t DW	% TREE	$/kg elemental	weighted value $/kg TREE
La	39.2	9.2%	$ 7.00	$ 0.65
Ce	95.6	22.4%	$ 7.00	$ 1.57
Pr	14.1	3.3%	$ 85.00	$ 2.81
Nd	65.0	15.3%	$ 60.00	$ 9.16
Sm	17.8	4.2%	$ 7.00	$ 0.29
Eu	4.4	1.0%	$ 150.00	$ 1.57
Sc	14.3	3.4%	$ 15,000.00	$ 504.32
Y	103.3	24.2%	$ 35.00	$ 8.49
Gd	24.2	5.7%	$ 55.00	$ 3.12
Tb	3.6	0.9%	$ 550.00	$ 4.68
Dy	20.2	4.7%	$ 350.00	$ 16.62
Ho	3.9	0.9%		
Er	10.2	2.4%	$ 95.00	$ 2.28
Tm	1.3	0.3%		
Yb	7.7	1.8%		
Lu	1.1	0.3%		
sum	425.9			$ 555.56

Scandium represents 82% of the metal value in AMD derived REEs. n=155

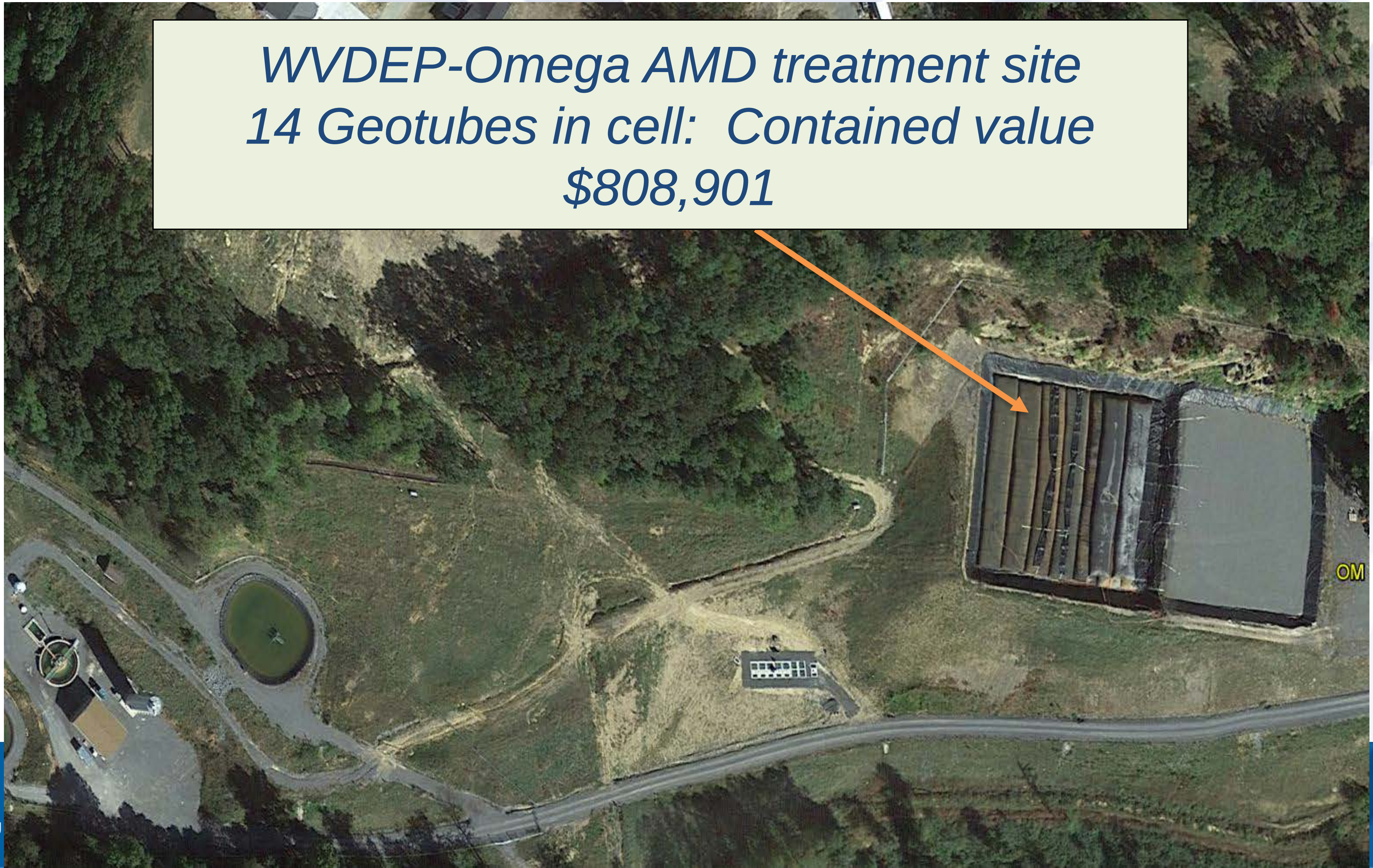


Contained sludge value=market value of REEs excluding transport and processing





Accessibility/Extractability/Dewatering



Estimated REE production CAPP/NAPP

Sludge cells sampled, this project			76
Sludge (Dry)		1,637,312	m^3
Sludge		3,602,086	tons DW
average TREE grade		708.5	g/t
TREE		**1,421**	**tons DW**
REE Basket Price (MREO)	$	237.23	/kg TREE
contained TREE value	**$**	**337,103,830**	

Estimated annual REE production: Appalachian Basin

		low		High	
AMD production		1,503,371		6,626,156	gpm
avg. TREE concentration		0.269		0.269	mg/L
Annual TREE production		807		3,555	tons/year
REE Basket Price (MREO)	$	237.23	$	237.23	/kg
Contained TREE value	**$**	**191,362,343**	**$**	**843,435,793**	**/yr**

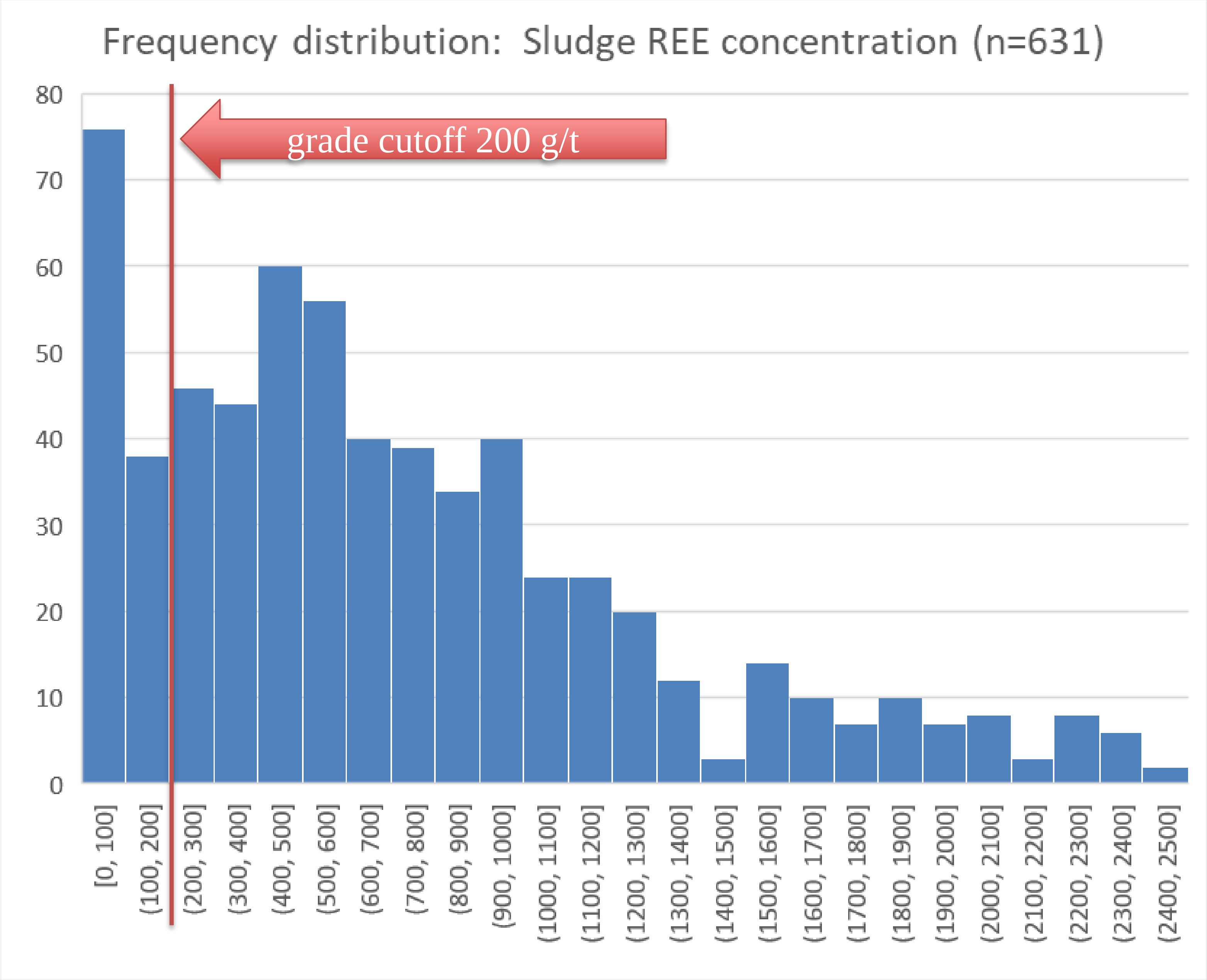
Summary: The AMD sludge resource

Key findings:

REE content, untreated coal mine AMD		
CAPP	233.5	µg/L
NAPP	304.2	µg/L
all	286.9	µg/L

REE content AMD sludge:		
CAPP	666.4	g/t
NAPP	750.6	g/t
all	708.5	g/t

Available REE stored at mines	
	1421 t
$	296 million



1. High proportion of heavy and critical REE: 45%, 60%

2. Very low U, Th <2%

3. Nearly as much Co as REE

	Sludge (g/t)		
	CAPP	NAPP	All
n =	144	485	629
La	79.2	58.3	68.7
Ce	160.7	162.5	161.6
Pr	23.7	24.3	24.0
Nd	104.3	113.8	109.0
Sm	26.4	32.0	29.2
Eu	6.4	8.4	7.4
Sc	12.6	20.9	16.7
Y	151.7	192.8	172.3
Gd	34.5	44.2	39.3
Tb	5.1	7.0	6.0
Dy	28.3	39.0	33.6
Ho	5.4	7.4	6.4
Er	14.2	19.9	17.0
Tm	1.9	2.8	2.3
Yb	10.4	15.1	12.8
Lu	1.6	2.3	2.0
TREE	666.4	750.6	708.5
LREE	400.8	399.2	400.0
HREE	265.6	351.4	308.5
HREE/TREE	**39.9%**	**46.8%**	**43.5%**
HREE+critical/TREE	**56.5%**	**63.1%**	**60.0%**
U	4.8	7.0	5.9
Th	6.6	7.5	7.0
U+Th/TREE	1.7%	1.9%	1.8%
Co	666.0	737.8	701.9

Valuation based on Mixed Rare Earth Oxides

Basket Price ($/kg TREE DW)		
CAPP	$	157.83
NAPP	$	258.40
Avg. all	$	237.23

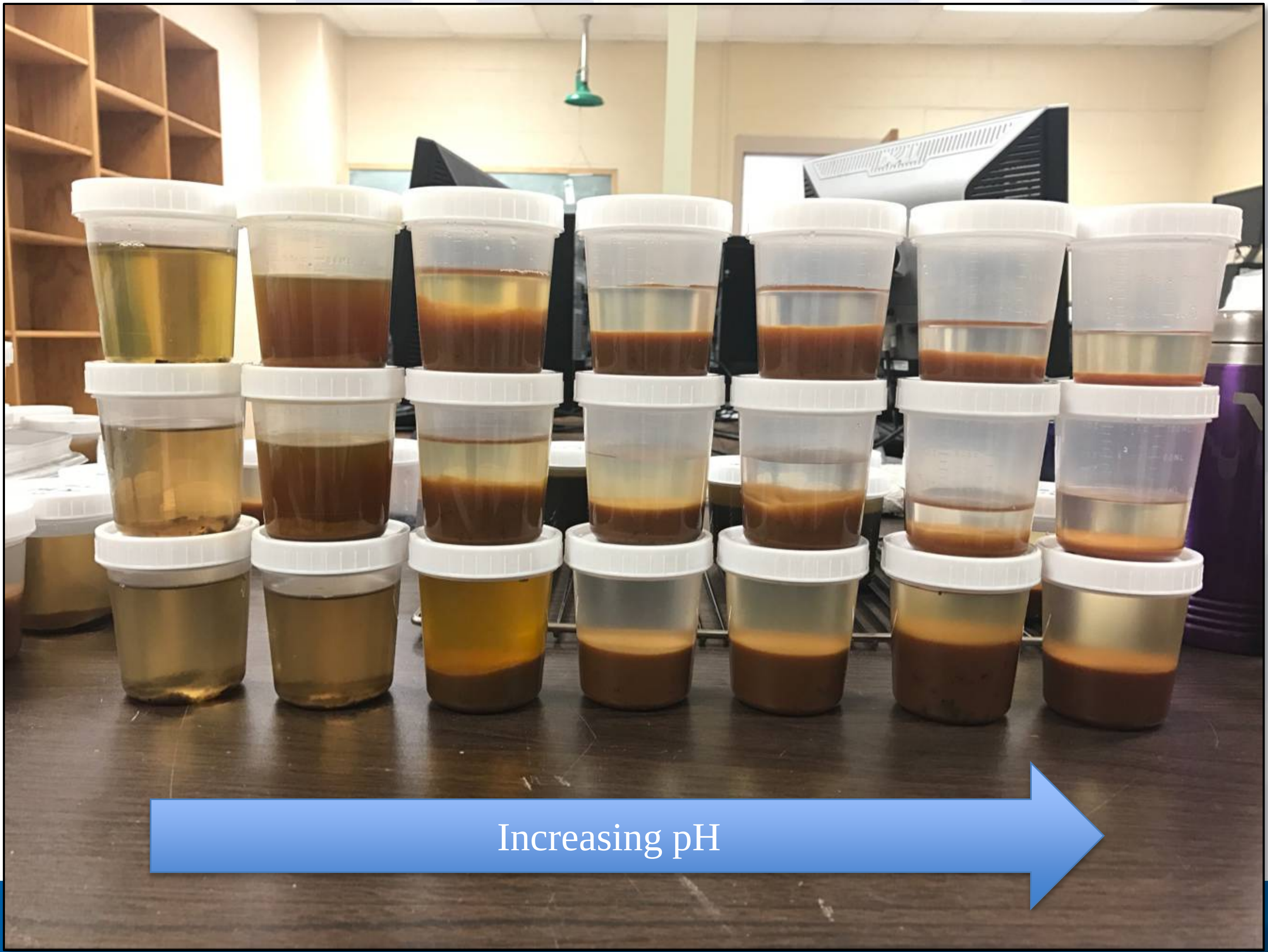
Contained REE Value ($/ton sludge DW)		
CAPP	$	107.50
NAPP	$	134.94
Avg. all	$	129.16

PROCESS DESIGN

AMD sludge cells, Mine 42 Windber PA

Steel Shaft sludge dissolved in H_2SO_4, pH 1

Separations Tests



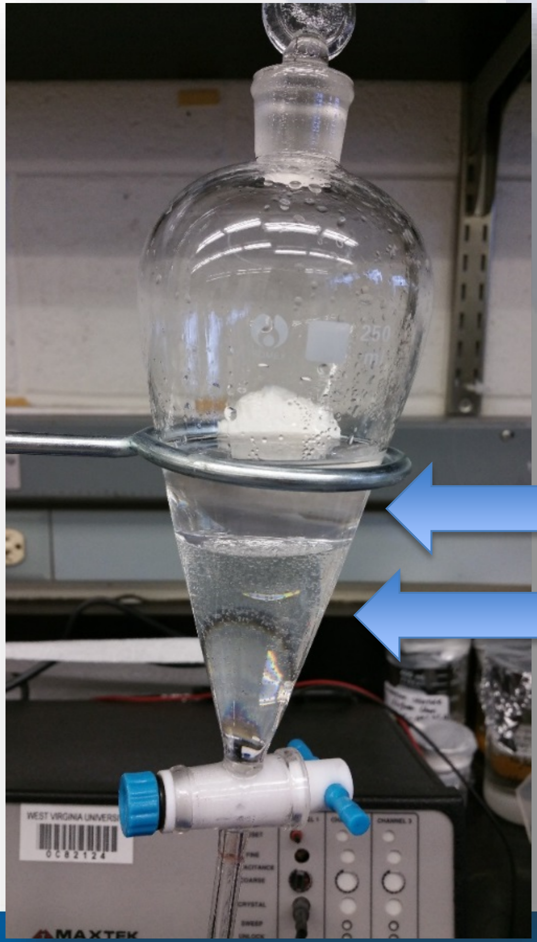
HCl

HNO3

H2SO4

Separations Test

Solvent Extraction in D2EHPA



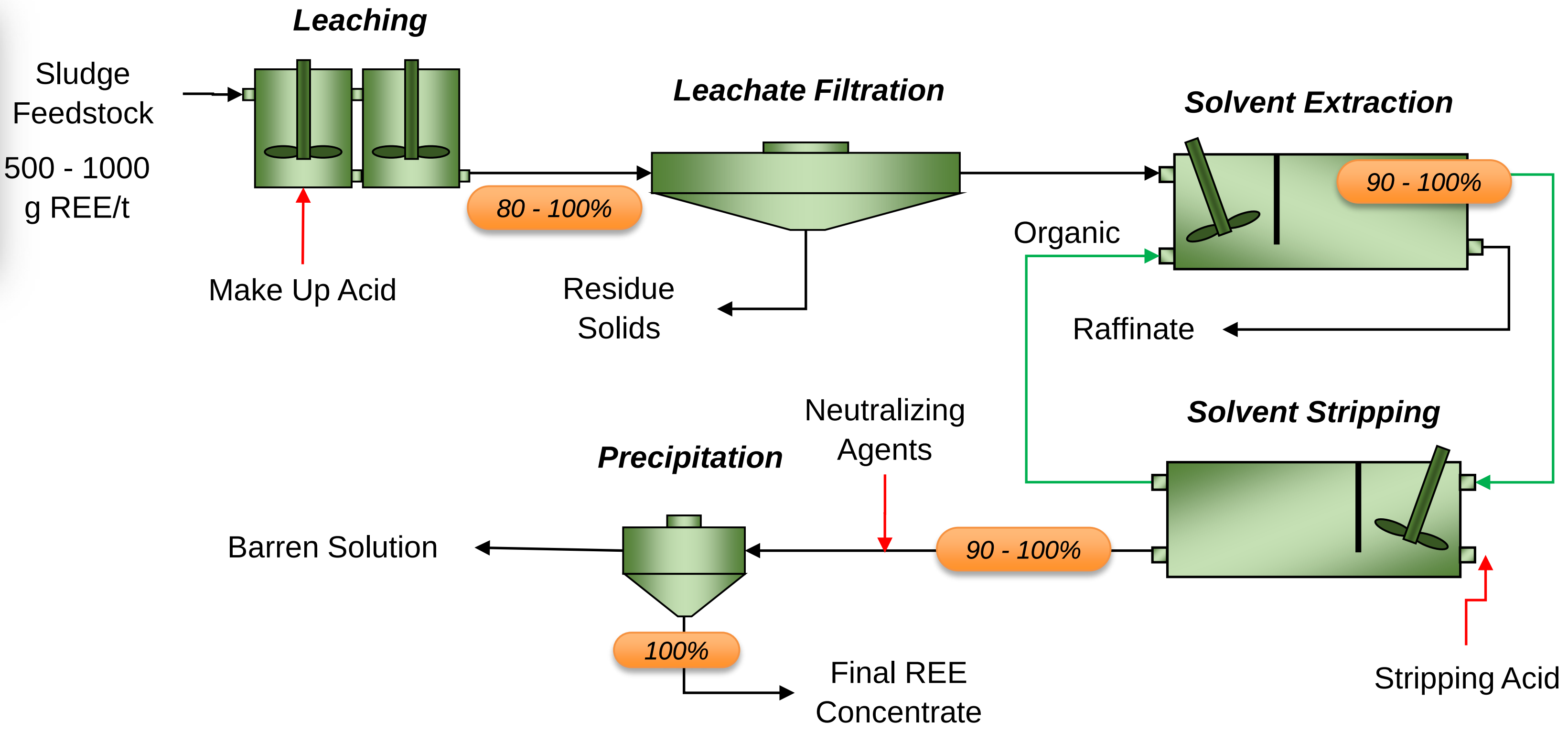
Organic Phase

Aqueous Phase

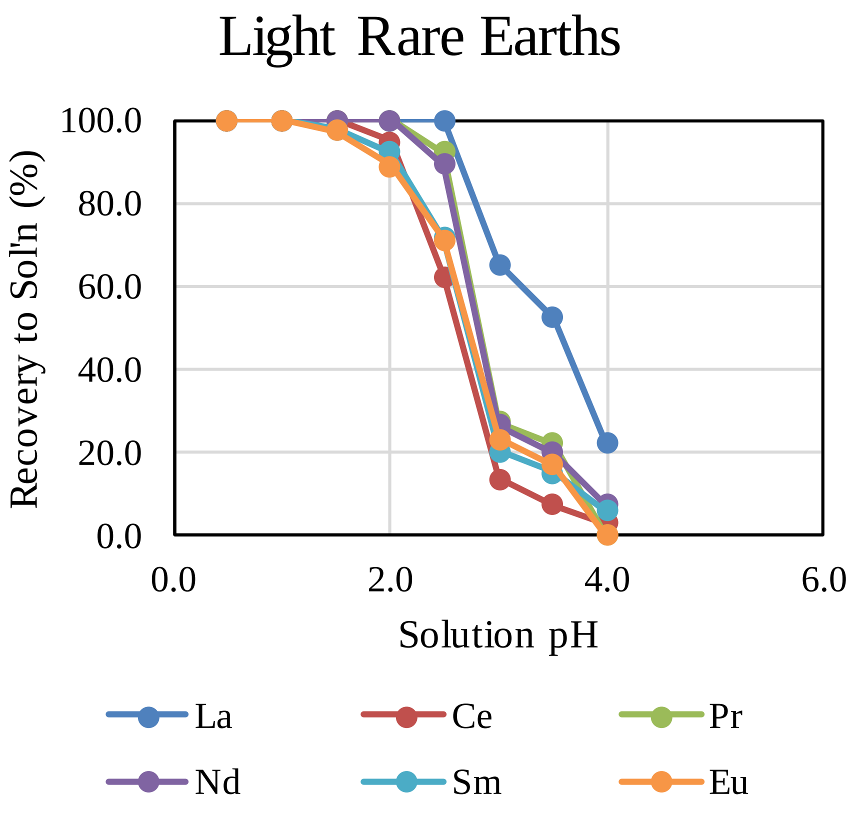
Conceptual Process Flowsheet

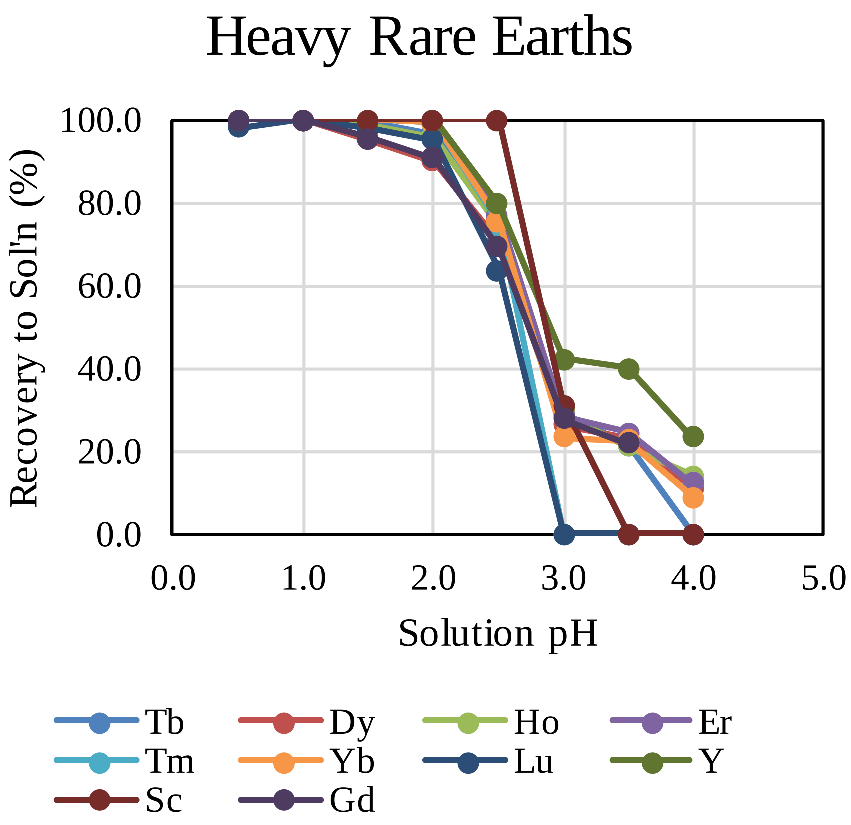
All processes at ambient pressure and temperature

REE recovery



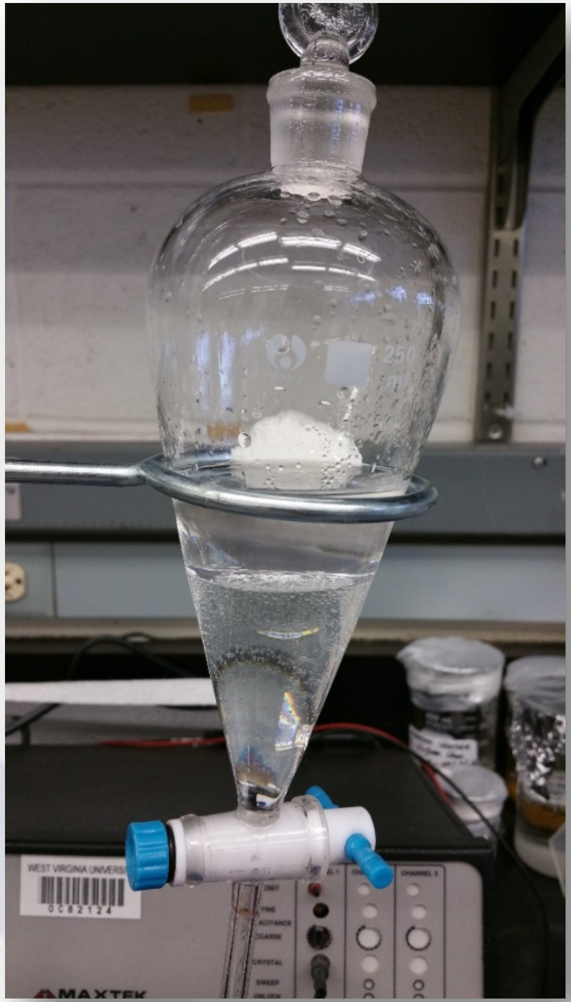
Acid Leaching at Ambient Temperature and Pressure





Feedstock

Solvent Extraction-Batch Tests



Distribution Coefficients (D)

- REE = 17.7 (as high as 100+ for some elements)
- Gangue Metal = 0.023

$$D = \frac{M_O}{M_{Aq}}$$

Separation Factor (SF)

- SF=17.7/0.023=770

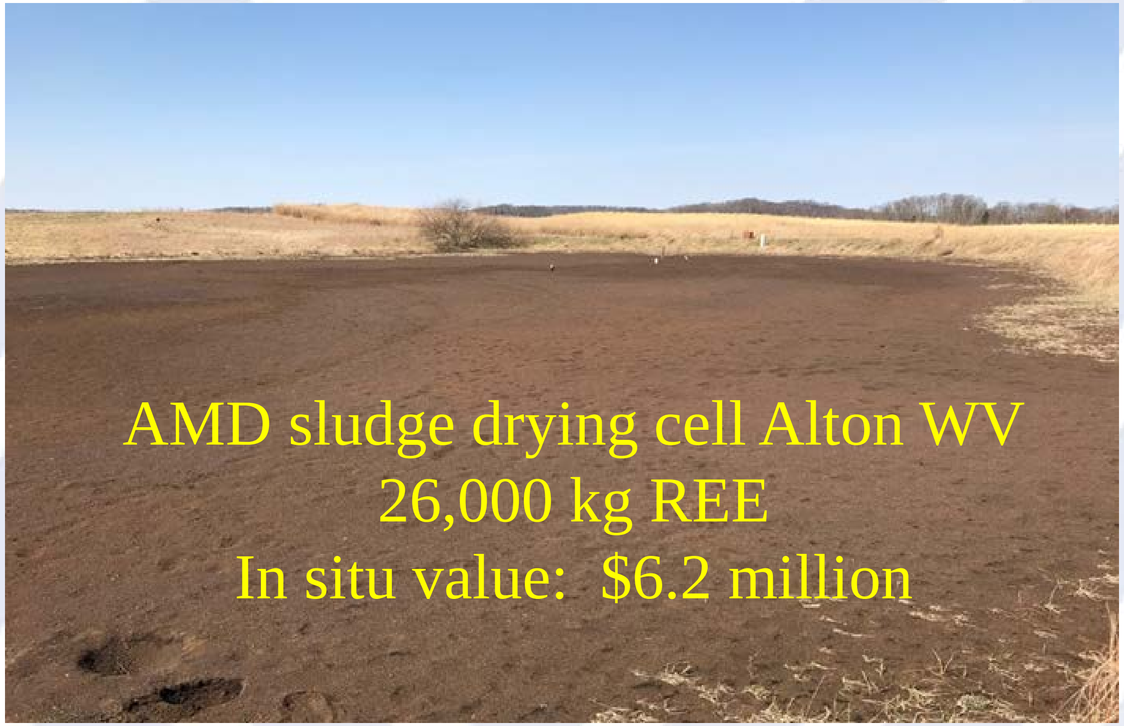
$$SF = \frac{D_{REE}}{D_{gangue}}$$

Construction
Bench-Scale, Continuous Flow Plant

SUMMARY

Summary

Acid from coal spoils, tailings, and underground mines tends to leach REEs from the surrounding rock.

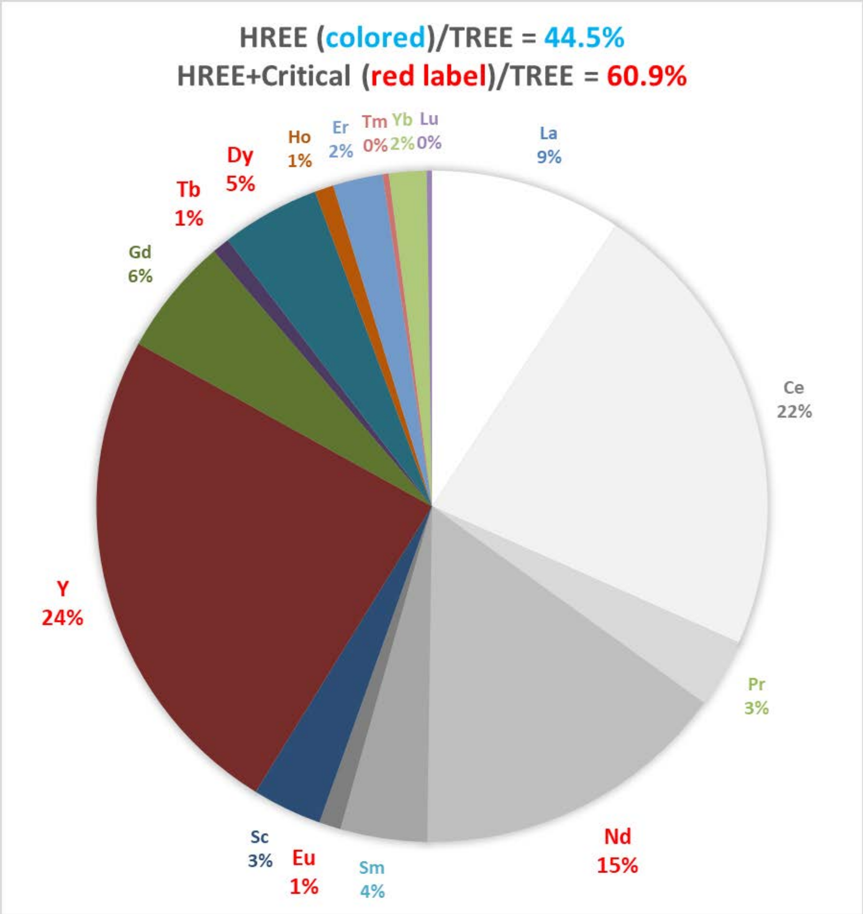


Conventional AMD treatment captures nearly 100% of the REEs and concentrates them by a factor of 2600x.

Summary

AMD sludge has a mean REE concentration of 420 g/t, with a fairly consistent elemental distribution. Excluding the lowest grades raises the average to >700 g/t.

High proportion of heavy and critical REEs



A continuous, bench scale ALSX unit is currently under construction. Operational early June 2018

Revenue potential: two scenarios

(we are in the early stages of optimizing the modular plant)

Parameter	modular plant 6.25 t/hr		Centralized plant 2100 t/day	
sludge feed grade	425 g/t, 65% moisture			
overall process recovery	87.20%			
weighted average metal quotation	$225/kg REE			
inherent value	$96/t plant feed			
realization	$6100/t concentrate			
REE concentrate production		1.36 t/day		29 t/day
internal rate of return		10%		46%
payback period (operating years		**18.5 years**		**2.5 years**
Net present value (1=10%)	$	47,217	$	63,454,000

Risk: REO, SREO

High confidence

- REE distribution
- REE grade
- Regional/local resource dimension
- Prediction based on site conditions

Low confidence

- Elemental separability through ALSX
- REO distribution through ALSX
- Processing costs
- Market
- Valuation

For more information, please contact:

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