Recovery of Rare Earth Elements (REEs) from Coal Mine Drainage

Paul Ziemkiewicz, Water Research Inst.
Xingbo Liu, Mechanical Engineering Dept.
Aaron Noble, Mining Engineering Dept.

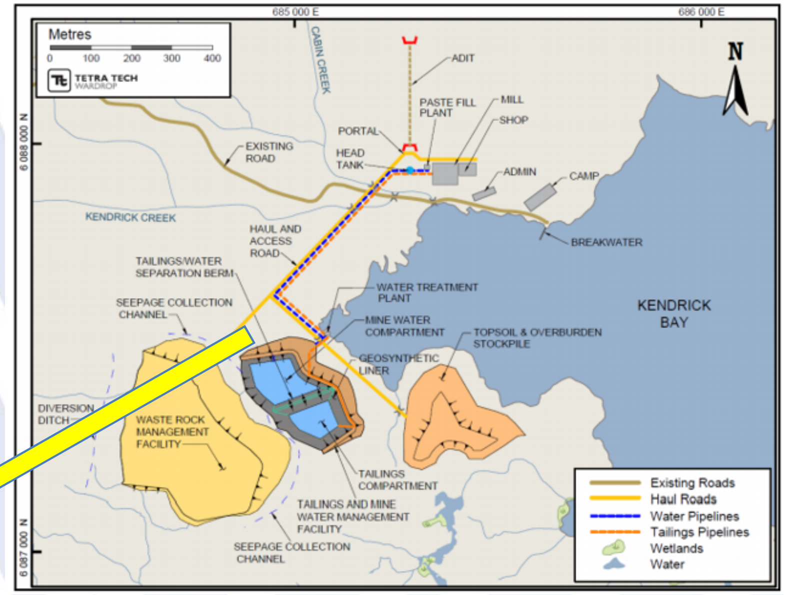
West Virginia University

NETL Cross Cutting Review
Pittsburgh PA
22 Mar 17

Global Demand, 2015

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

Figure 1.2 General Site Layout



Current, proposed developments

% Total REE, Proposed Developments

concentration	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

Project ETD30: characterization and extraction economics

Phase 1.

1. Development of a cost-effective & environmentally benign process to treat and recover REEs from AMD
2. Preliminary process system design and techno-economic analysis in preparation for pilot-scale testing
3. Down select by USDOE/NETL

Phase 2.

1. Build and operate a pilot plant
2. Report cost/performance

Participants

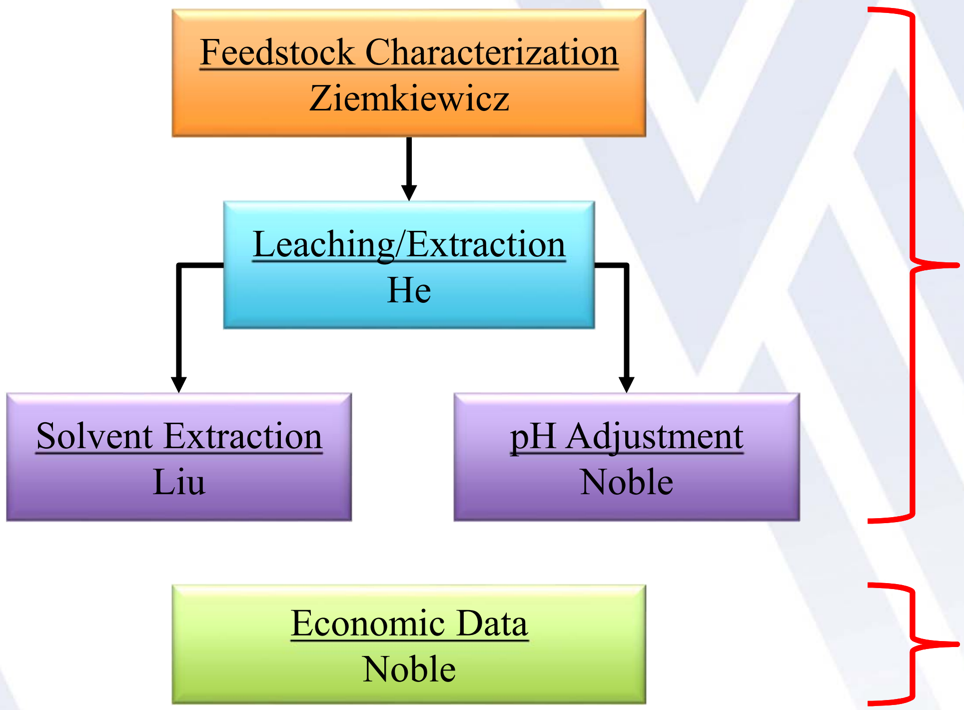
WVU

- Paul Ziemkiewicz, PhD
  - Director, WVU Water Research Institute
- Xingbo Liu, PhD
  - Professor, Mechanical and Aerospace Engineering
- Aaron Noble, PhD
  - Assistant Professor, Mining Engineering

External

- Mepco Inc.
- Rosebud Mining Co.
- West Virginia Dept. of Environmental Protection
- Alliance Coal Corp.
- Consol Energy, Inc.

Project Outline



Interpret all data using n^{th} order kinetics, with respect to experimental conditions and feedstock characterization.

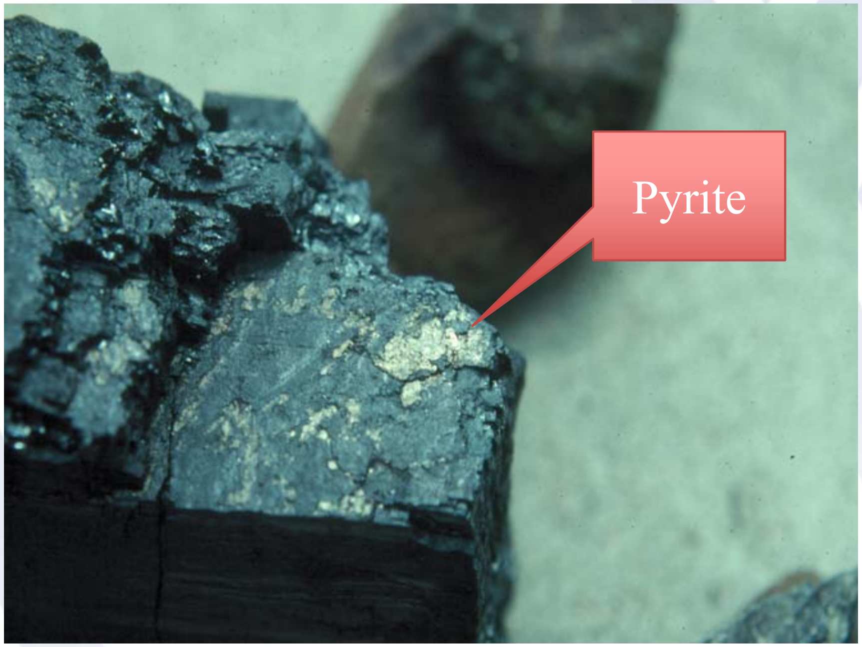
Develop and maintain database.

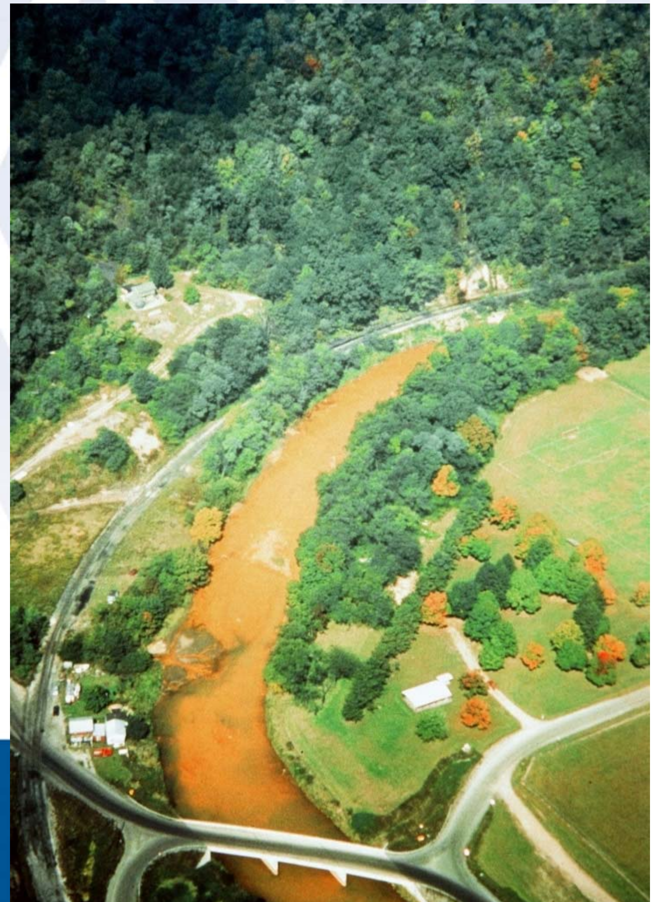
Acid Mine Drainage: AMD

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

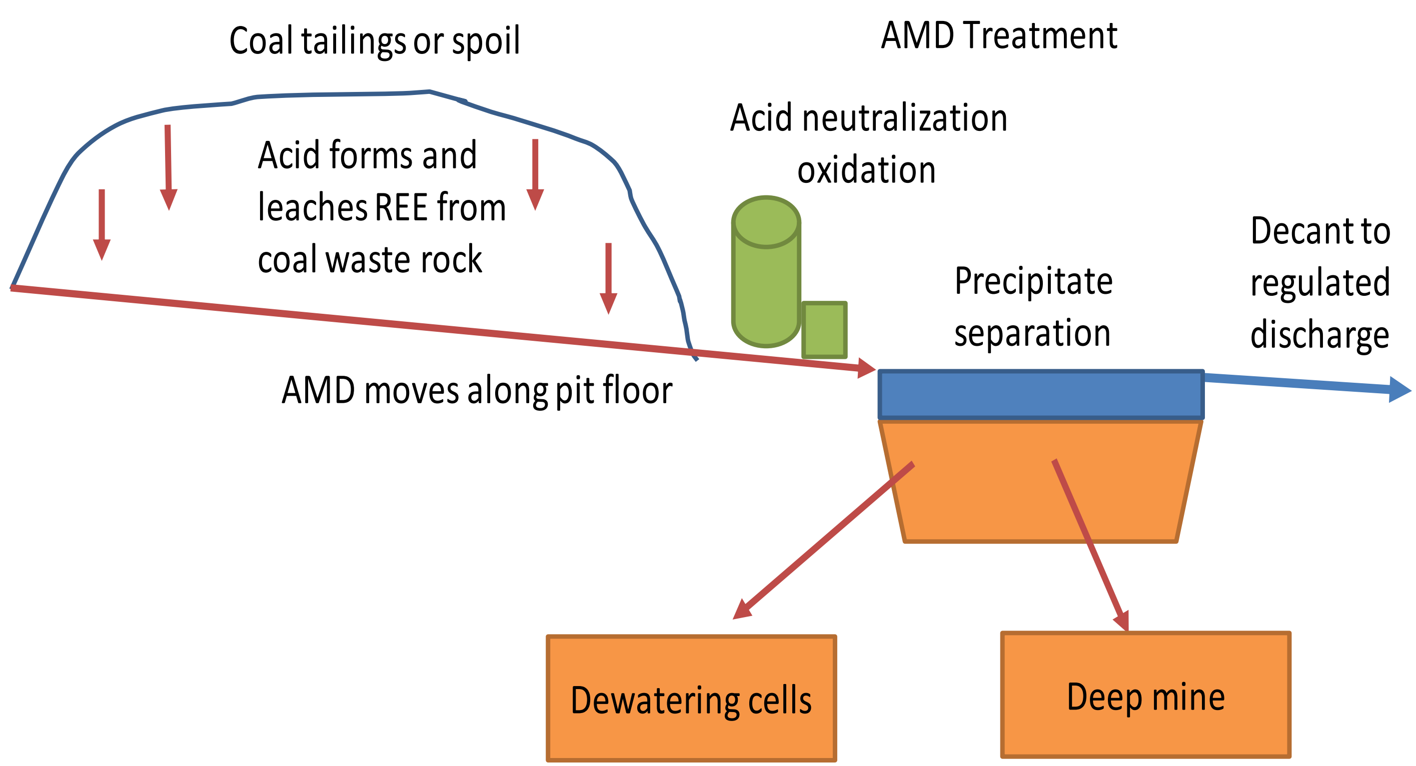
Pyrite + O_2 + H_2O
= Fe^{2+} + H_2SO_4

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





Typical AMD treatment layout



AMD treatment

2. Lime for pH adjustment

1. RAW AMD= **water** + **major ions (Ss)** + **TREE**

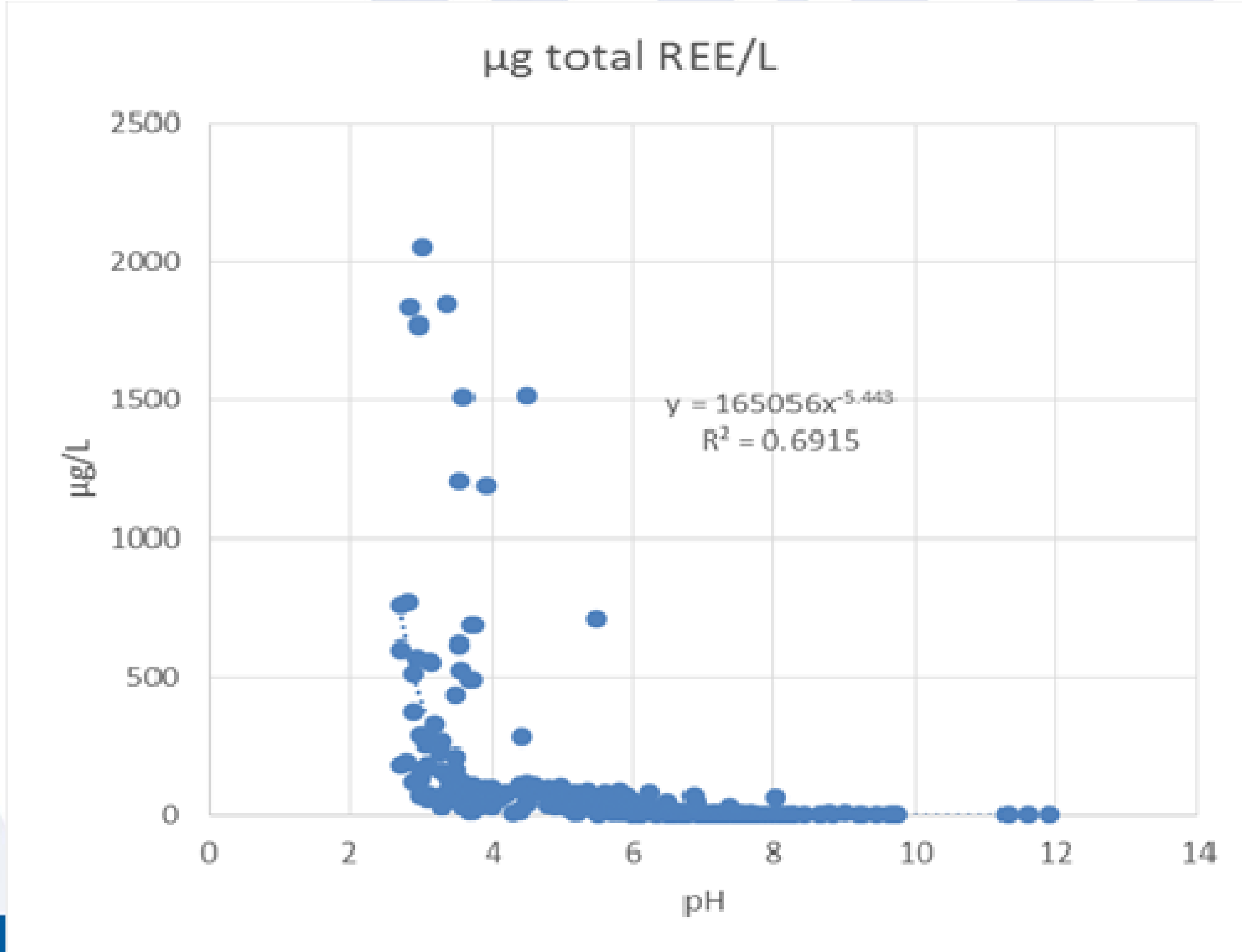
3. AMD treatment: lime mixing/oxidation

5. Treated **water** for surface discharge

4. AMD sludge: precipitation of **major ions (Ss)** + **TREE**

Typical AMD Treatment Facility

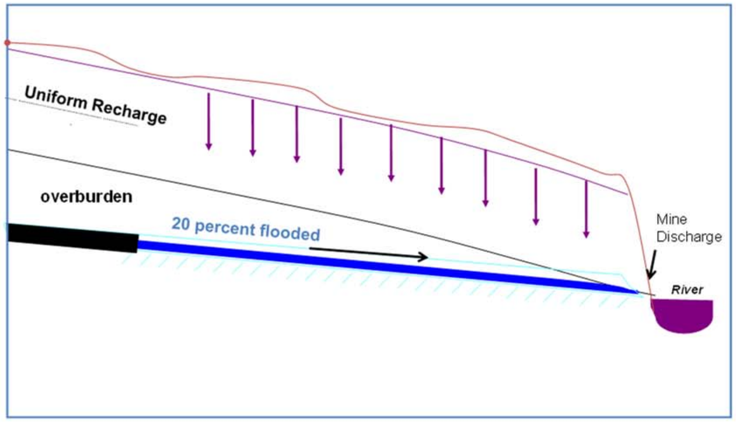
Acid mine drainage:
TREE Concentration vs. raw water pH



The extraction point will control REE concentration

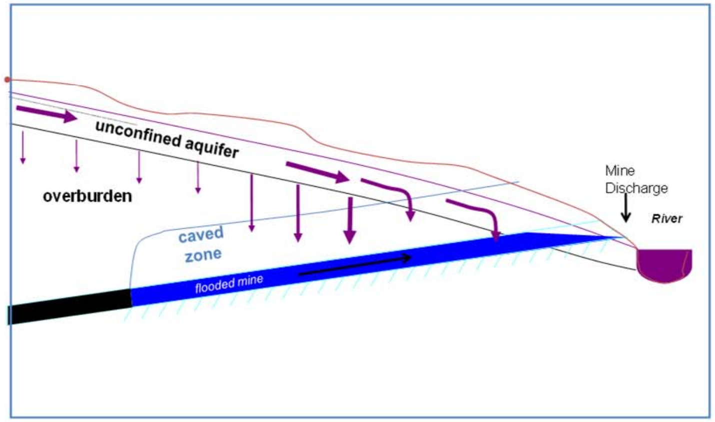
Low pH/hi REE

Unflooded, Free Draining

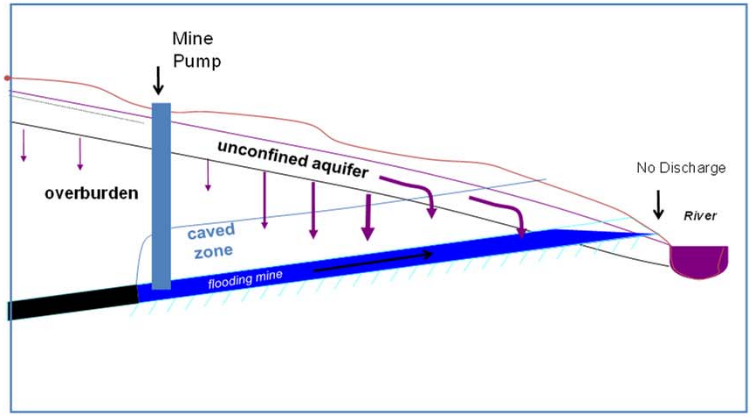


High pH, low REE

Flooded High Dilution



Flooded Mine Low Dilution



Heavy REEs are more valuable than light REEs

Average: Spring and Fall 2016 samples

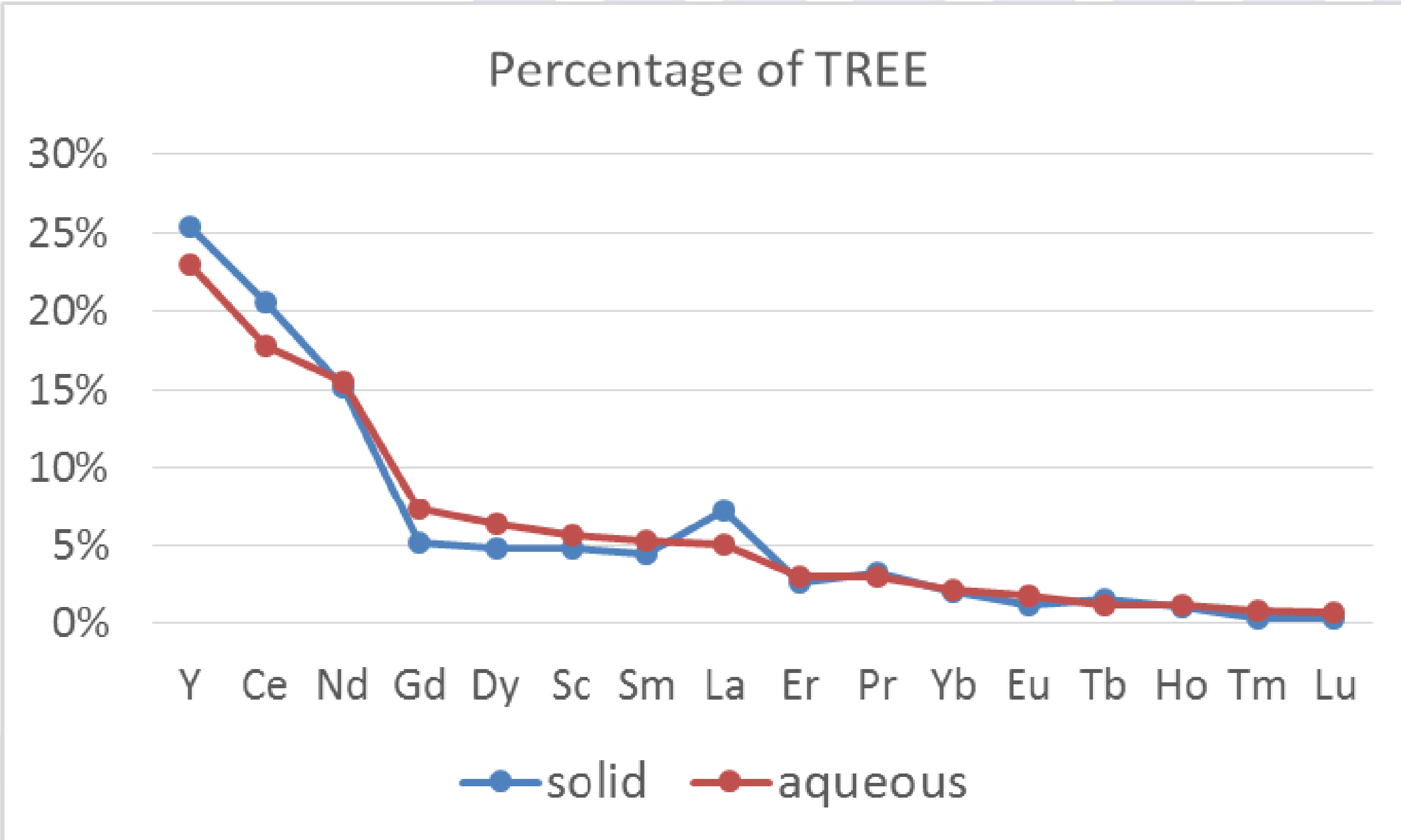
Raw AMD

site	TREE µg/L	% heavy REEs
SM	72	51%
MV	1769	48%
DL	98	41%
OM	297	40%
TT	189	38%
VK	371	34%
BM	147	27%
all sites n=16	421	40%

AMD precipitates

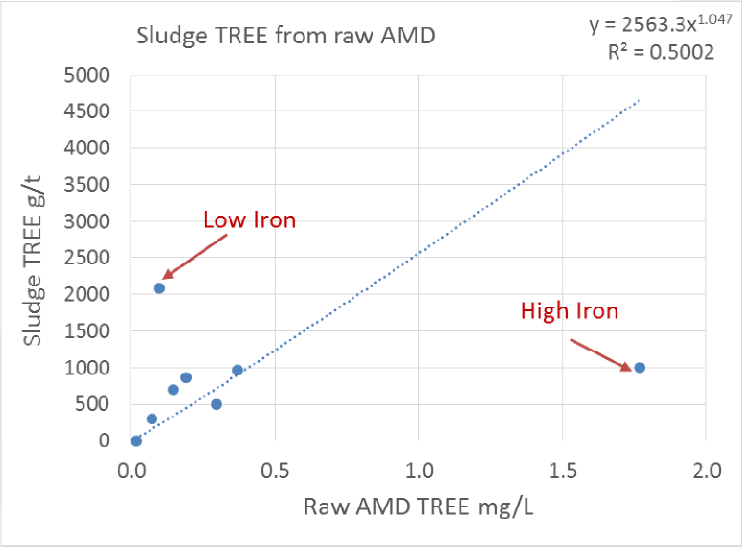
site	TREE g/t	% heavy REEs
SM	172	46%
DL	1352	40%
OM	370	39%
MV	688	38%
TT	664	37%
VK	715	36%
BM	577	29%
all sites, n=49	648	38%

All REEs precipitate to AMD solids with nearly equal enthusiasm

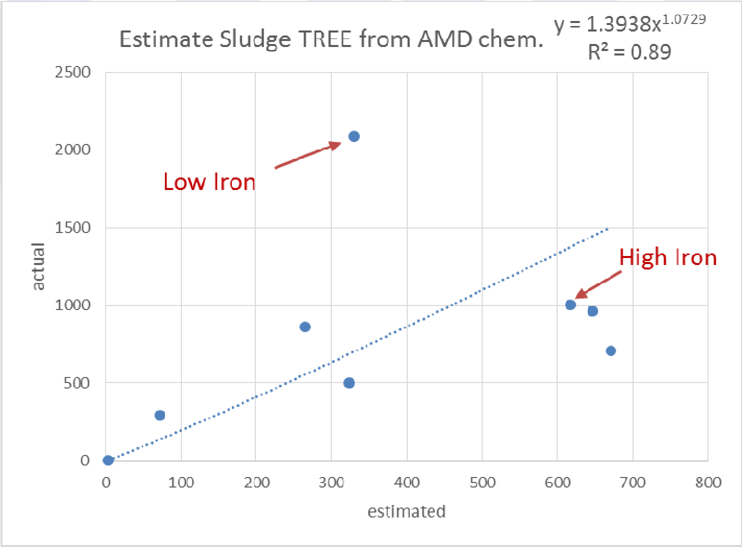


AMD treatment concentrates REEs by 1,500x. Precipitate concentrations can be predicted.

Raw AMD vs. Precipitate R^2=0.5



AMD chem. vs. Precipitate R^2=0.89



Inherent value of Rare Earth Elements in AMD solids at seven treatment sites

average 2 samples site	raw TREE mg/L	actual Solids TREE g/t	Q gpm	REE load tpy	REE value* $/yr
A	0.07179	296	4,000	0.57	$ 89,353
B	1.76875	1002	156	0.55	$ 85,863
C	0.18898	859	1,200	0.45	$ 70,567
D	0.37120	964			
E	0.01619	3	4,500	0.15	$ 22,664
F	0.09832	2086	600	0.12	$ 18,357
G	0.29738	499	90	0.05	$ 8,329
H	0.14710	708	60	0.02	$ 2,746
			10,606	**1.91**	**$ 297,879**

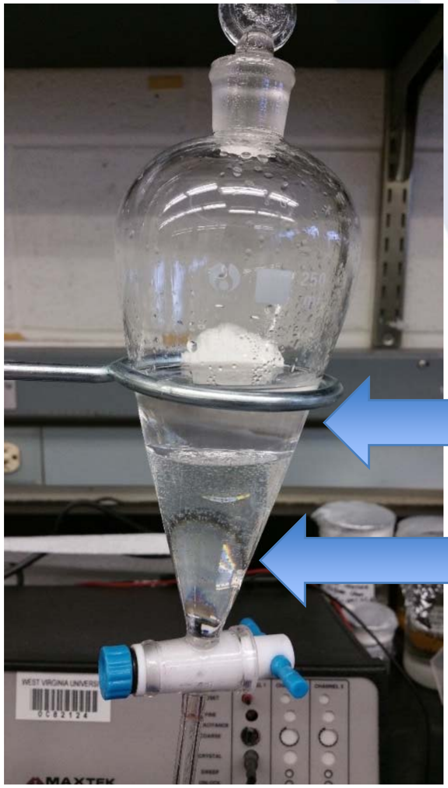
*Inherent AMD solids value (per kg): **$ 155.95**

Sludge dewatering using Geotubes: WVDEP/Omega

Steel Shaft sludge dissolved in H_2SO_4, pH 1

Separations Tests

Separations Test



Solvent Extraction in D2EHPA

Organic Phase

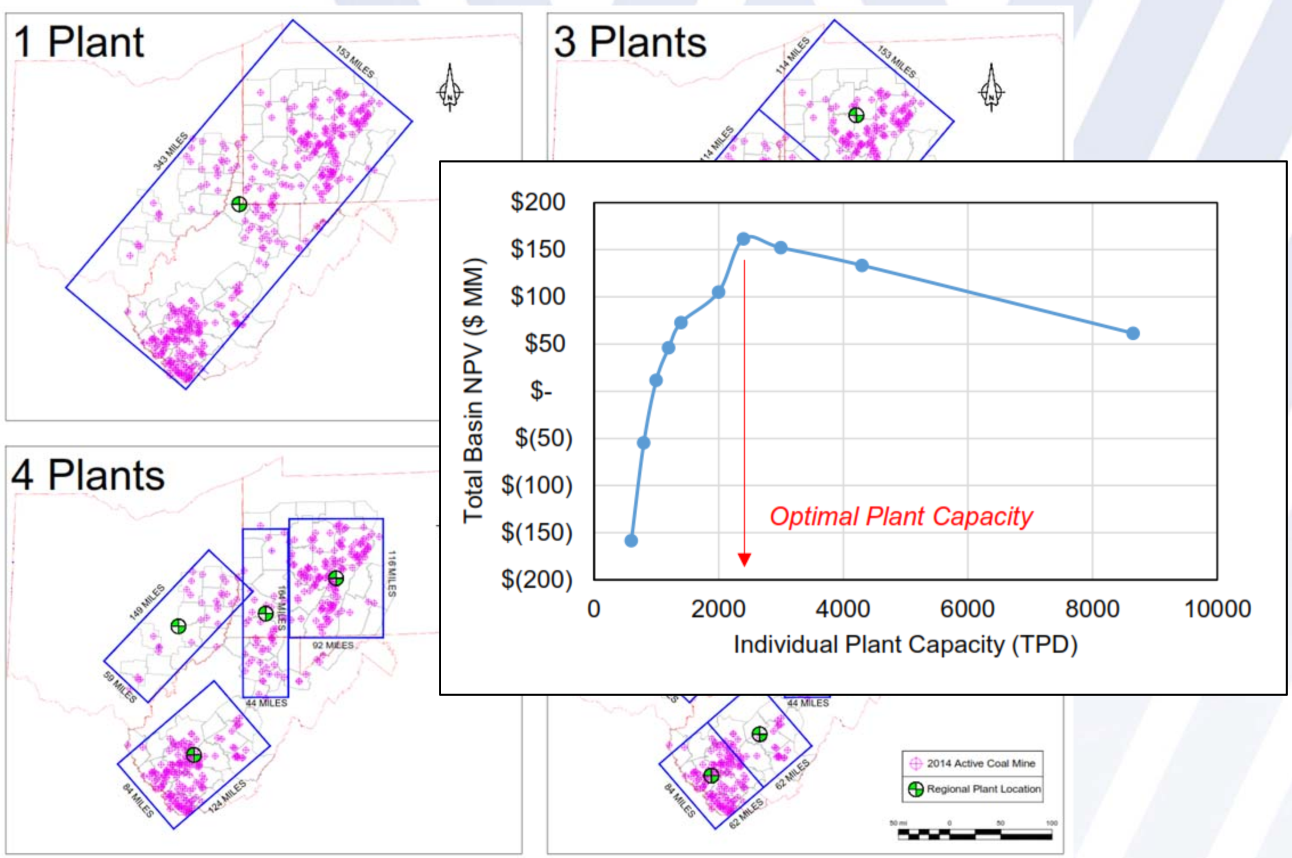
Aqueous Phase

Regional Value Model

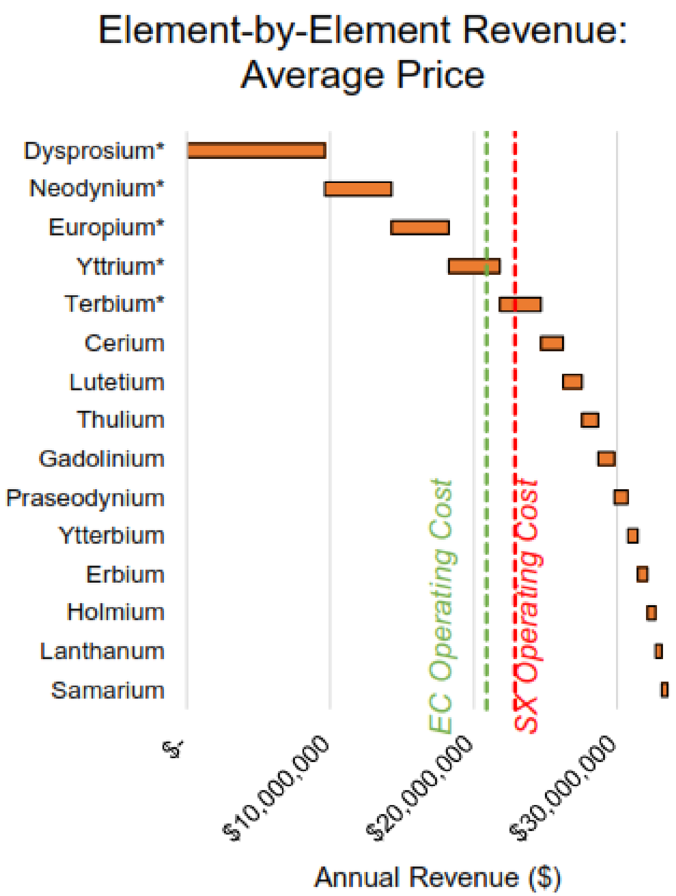
Regional TREE value model: Northern Appalachian Coal Basin

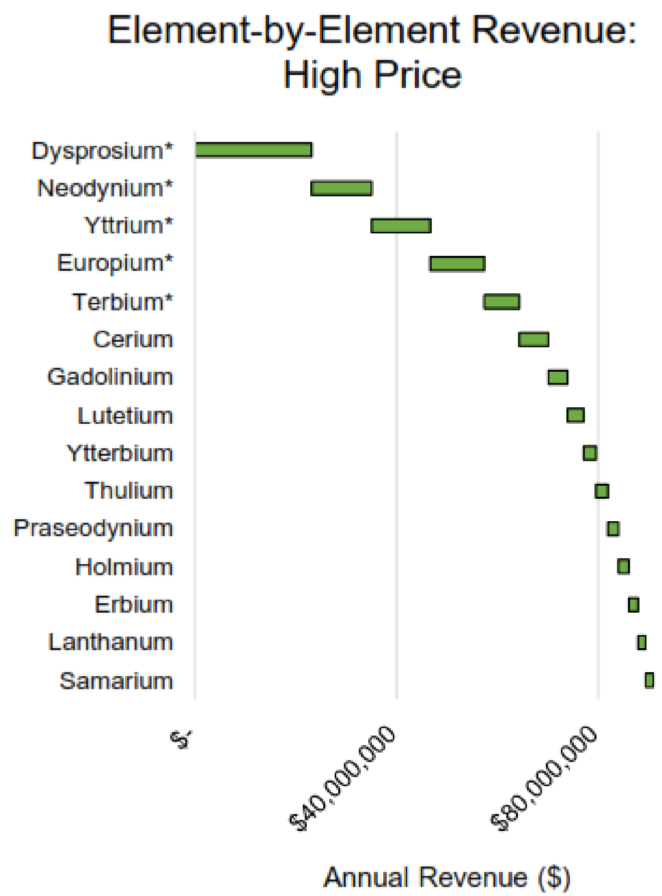
VARIABLES	raw AMD		500,000	gpm
	raw AMD		1,893	cu M/min
	sludge/AMD		7.5%	vol/vol
	solids/sludge		3%	vol/vol
	Ss density		1,055	kg/cu M
	TREE/Ss		648	g/t
	TREE value	$	155.95	/kg TREE
OUTPUT	Ss		4.26	cu M/min
	Ss		4,493	kg/min
	Ss		2,361,414	tons/yr
	TREE production		1,530,196	kg/yr
	value	$	238,634,099	/yr
AMD TREATMENT	unit cost	$	1.00	/1000 gal
	annual cost	$	262,800,000	/yr
Average prices from 2011 to 2015 inclusive		$	155.95	/kg TREE
Based on weighted REE content of AMD solids				

Centralized Refinery Scenarios



Revenue Estimate (2,100 TPD Plant)



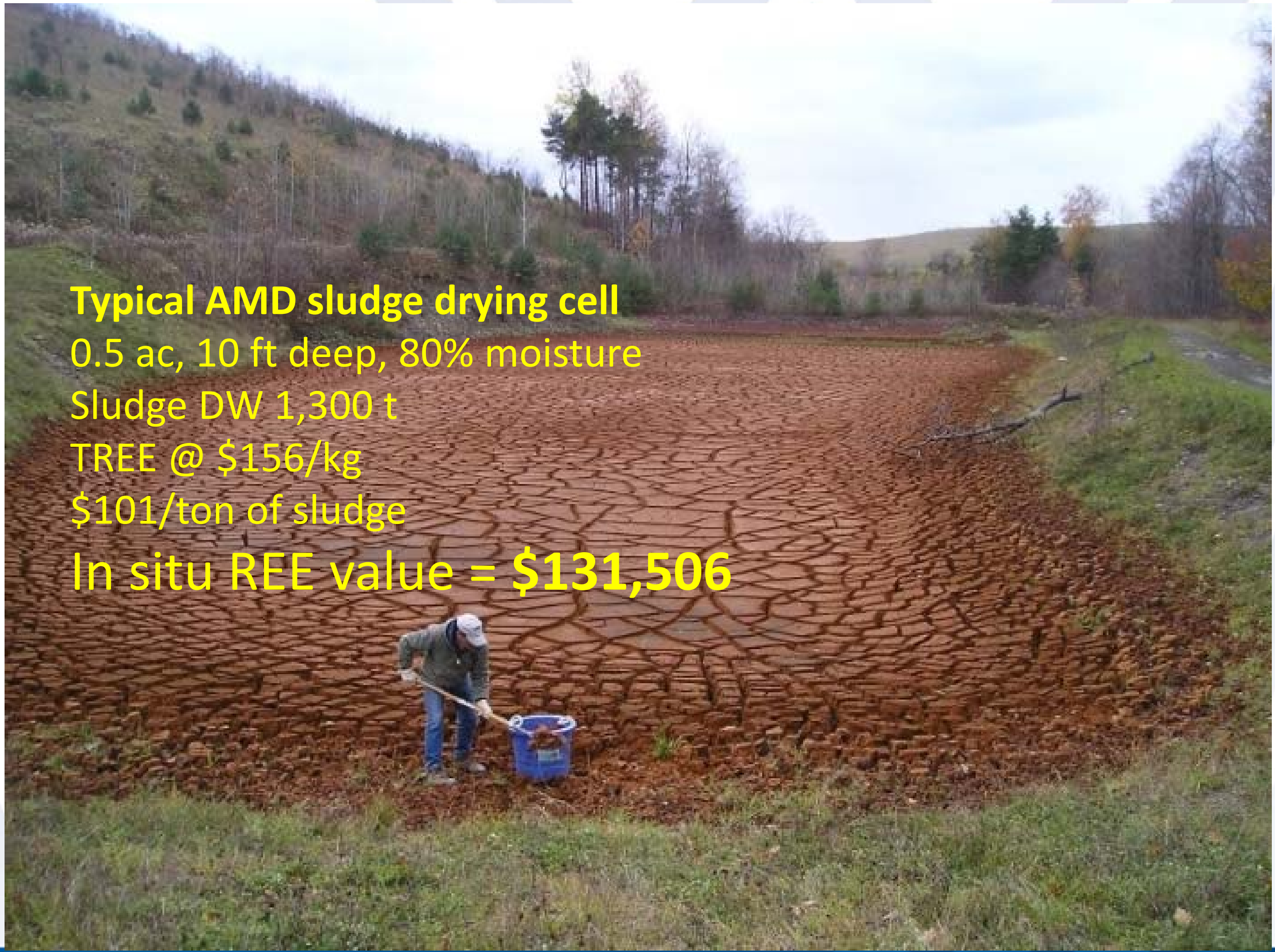


Annual cash flow 2,400 tpy plant
Estimated payback period 5.5 years

Table 25: Annual Cash Flow for Reference Case Flowsheet

Period (Year End)	0	1	2	...	25
Sales Revenue ($/yr)	**$ -**	**$ 33,506,886**	$ 33,506,886		**$ 33,506,886**
- Operating Costs	**$ -**	**$ 22,893,259**	$ 22,893,259		**$ 22,893,259**
Taxable Income ($/yr)	**$ -**	**$ 10,613,627**	$ 10,613,627		**$ 10,613,627**
- Income Tax	$ -	$ 3,608,633	$ 3,608,633		$ 3,608,633
Net Profit/Loss ($/yr)	**$ -**	**$ 7,004,994**	$ 7,004,994		**$ 7,004,994**
+ Depreciation	$ -	$ 1,185,629	$ 1,185,629		$ 1,185,629
Cash Flow ($/yr)	**$ -**	**$ 8,190,623**	$ 8,190,623		**$ 8,190,623**
- Capitalized Cost	$ 34,383,238	$ -	$ -		$ 4,742,516
Net Cash Flow ($/yr)	**$ (34,383,238)**	**$ 8,190,623**	**$ 8,190,623**		**$ 12,933,138**
Discounted Cash Flow (i=10%)	$ (34,383,238)	$ 7,446,021	$ 6,769,110		$ 1,193,677
Cumulative DCF	**$ (34,383,238)**	**$ (26,937,218)**	**$ (20,168,108)**		**$ 40,401,086**

In situ sludge value=market value of REEs excluding transport and processing



In situ value of two WVDEP/OSR AMD precipitate storage cells

County	Monongahela		Upshur	
OSR site	VMS		DLM	
Input				
grade		400	2086	g TREE/t
area		1.5	2.3	ac
depth		10	10	ft
solids		20%	20%	
Constants/calculations				
volume		18,502	28,370	m^3
unit value (DW)*	$	62.38	$ 325.31	/t
density (DW)		1055	1055	kg/m^3
mass (DW)		3,904	5,986	t
mass TREE		1,562	12,487	kg TREE
Inherent value (DW)	$	155.95	$ 155.95	$/kg TREE
in situ value	**$**	**243,529**	**$ 1,947,341**	

*Dry weight

Project ETD39: Regional Sampling

- Objective: Identify whether there is sufficient AMD based Rare Earth resource to sustain a significant industry in the Eastern Coal Fields.
- Focus: NAPP, CAPP
- Need: Access to Raw AMD samples and sludge, Discharge volume…
- Anonymized sampling: Disclosure only with owner's permission
- Key person: **Ben Faulkner**

benbfaulkner@gmail.com

Questions?

Paul Ziemkiewicz, PI
Director, WVU Water Research Institute
Morgantown WV
pziemkie@wvu.edu
304 293 6958

NATIONAL ENERGY TECHNOLOGY LABORATORY