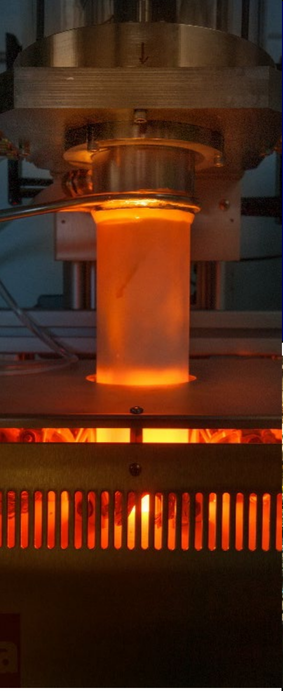
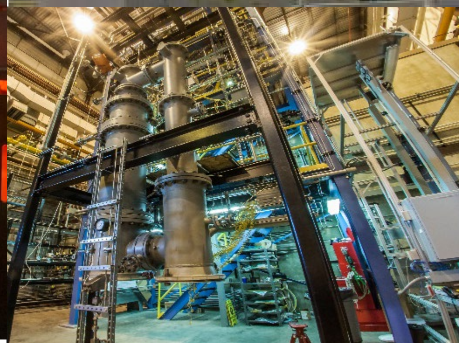
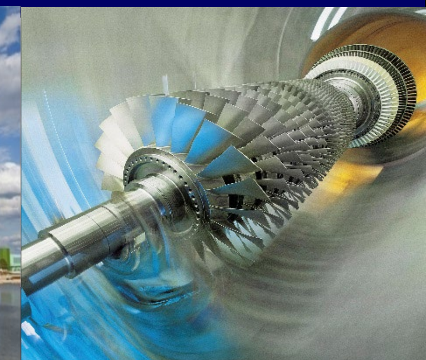



U.S. DEPARTMENT OF ENERGY | Office of Fossil Energy



Demonstration of Scaled-Production of Rare Earth Oxides and Critical Materials from U. S. Coal-Based Sources

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Josh Werner, Co-Principal Investigator, UKY
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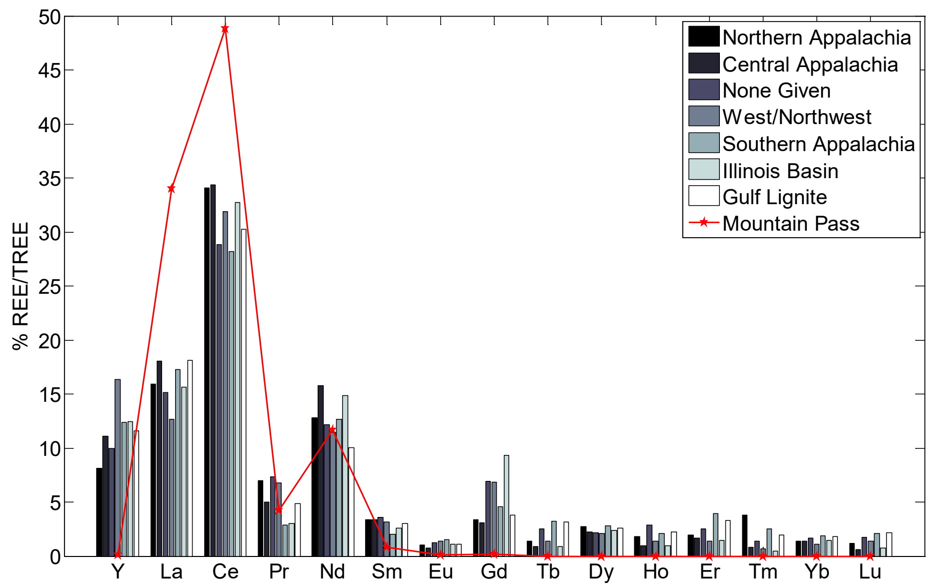
Partners: University of Kentucky, University of Utah, Virginia Tech, Alliance Coal, Kentucky River Properties, Mineral Separation Technologies

August 2020

PROJECT OBJECTIVES AND SUPPLY CHAIN

- **Demonstration of scaled production of high purity rare earth oxide mix from coal refuse sources using innovative technologies that will reduce cost and improve environmental outcomes.**
- **Performance objectives:**
  - >90% REO mix purity
  - 200 g/day product rate
  - Co, Li, Mn and Sc products >2% purity
  - Cost reduction per kg of REO produced by 50%
- **Bituminous coarse coal refuse sources will be the primary feedstock.**

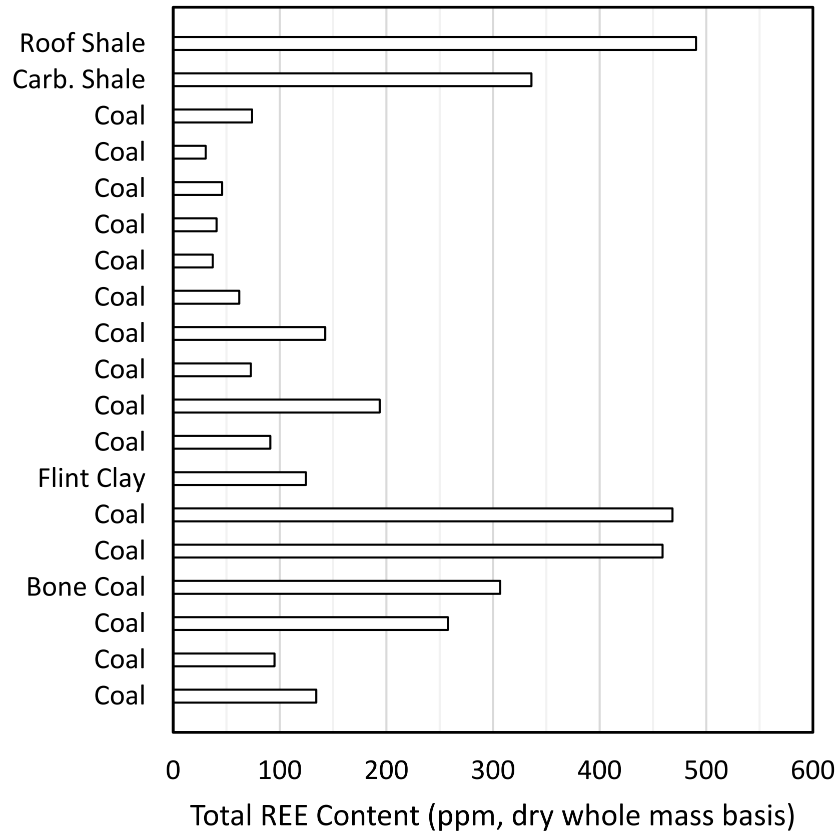


Basin	HREE/TREE
Central Appalachia	27%
Northern Appalachia	30%
West/Northwest	36%
Southern Appalachia	40%
Illinois Basin	34%
Gulf Lignite	36%

** Source: USGS Coal Quality Database*

PROJECT DISCUSSION: FEEDSTOCK

Vertical REE Distribution: Fire Clay



Stream	Mass TPY	REE TPY
Plant Feed	78,567,376	9,899
Clean Coal	36,697,676	1,620
Coarse Refuse	33,279,712	6,285
Fine Refuse	8,589,993	1,313

- Survey of 20 eastern U.S. Coal Preparation Plants
- Luttrell et al., 2019

PROJECT DISCUSSION: FEEDSTOCK

- **Baker (WK No. 13): 1.6 billions tons > 42 in.**
- **17.5 million tons coarse coal refuse**
- **4600 mt of REEs, 480 tons of heavy REEs**
- **10,000 tons of other CM**
- **Estimated total value = $1.4 billion**

Category	Element	Content (ppm)	Resource (tonnes)	Market Value ($*10^6)
Light	Sc	16	273	$1,108.58
	La	47	831	$4.82
	Ce	99	1738	$10.08
	Pr	12	206	$21.39
	Nd	47	814	$56.65
	Sm	14	247	$4.74
	Eu	2	31	$1.09
Heavy	Y	3	57	$2.22
	Gd	7	131	$30.32
	Tb	1	13	$11.35
	Dy	4	77	$30.83
	Ho	2	41	$2.70
	Er	5	81	$2.59
	Tm	1	12	$20.12
	Yb	3	57	$6.60
	Lu	1	12	$10.41
Other CM	Co	18	318	$10.03
	Li	190	3324	$31.25
	Mn	227	3966	$3.97
	V	131	2298	$25.28

PROJECT DISCUSSION: FEEDSTOCK

- **Fire Clay (Hazard No. 4): 1.1 billion tons > 28”**
- **90.0 million tons coarse coal refuse**
- **29,000 mt REEs and 4,650 mt (16%) heavy REE**
- **10,000 tons of other CM**
- **Estimated total value = $6.9 billion**

Category	Element	Content (ppm)	Resource (tonnes)	Market Value ($*10^6)
Light	Sc	17	1554	$5,441.88
	La	53	4808	$24.04
	Ce	122	10937	$54.69
	Pr	14	1296	$115.70
	Nd	51	4632	$277.93
	Sm	11	994	$16.47
	Eu	2	155	$4.66
Heavy	Y	25	2276	$76.40
	Gd	10	867	$173.32
	Tb	0	44	$33.35
	Dy	6	530	$183.59
	Ho	2	159	$9.07
	Er	5	417	$11.54
	Tm	1	83	$124.99
	Yb	3	273	$27.34
	Lu	0	2	$1.40
Other CM	Co	23	2106	$66.48
	Li	174	15625	$146.87
	Mn	278	25033	$25.03
	V	140	12557	$138.13

PROJECT DISCUSSION: FEEDSTOCK

Coarse Refuse Heap Leach Solution

Elemental Analysis

Element	PPM
Sc	0.78
Y	3.90
La	0.31
Ce	2.25
Pr	0.88
Nd	1.09
Sm	0.62
Eu	0.19
Gd	2.65
Tb	0.29
Dy	0.95
Ho	< 0.003
Er	0.01
Tm	0.09
Yb	0.31
Lu	0.14
Total	**14.45**

Element	PPM
Th	<0.003
U	1.53
Fe	5453
Al	1467
Ca	459
Mg	572
Mn	77.6

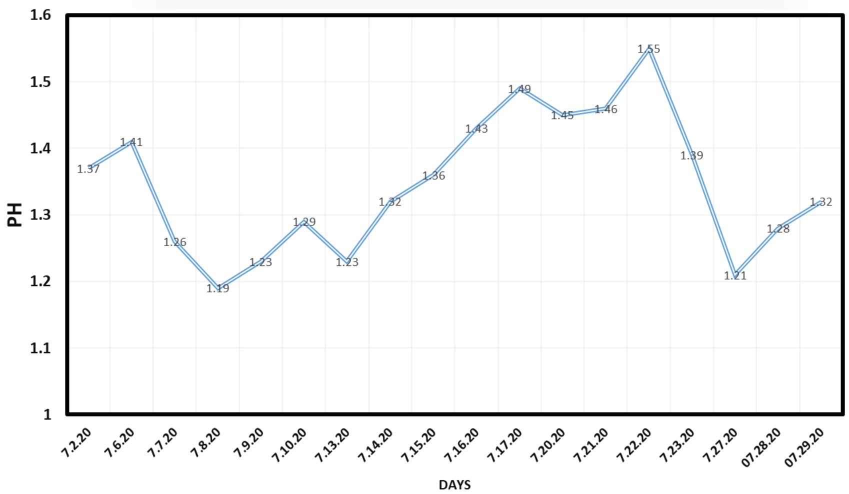
PROJECT DISCUSSION: ASSOCIATED MINERAL ADVANTAGE

- **Coal is associated with minerals that provide natural acidity and alkalinity:**
  - Pyrite
  - Calcite
- **Both minerals have physical properties that allow low cost recovery and concentration.**

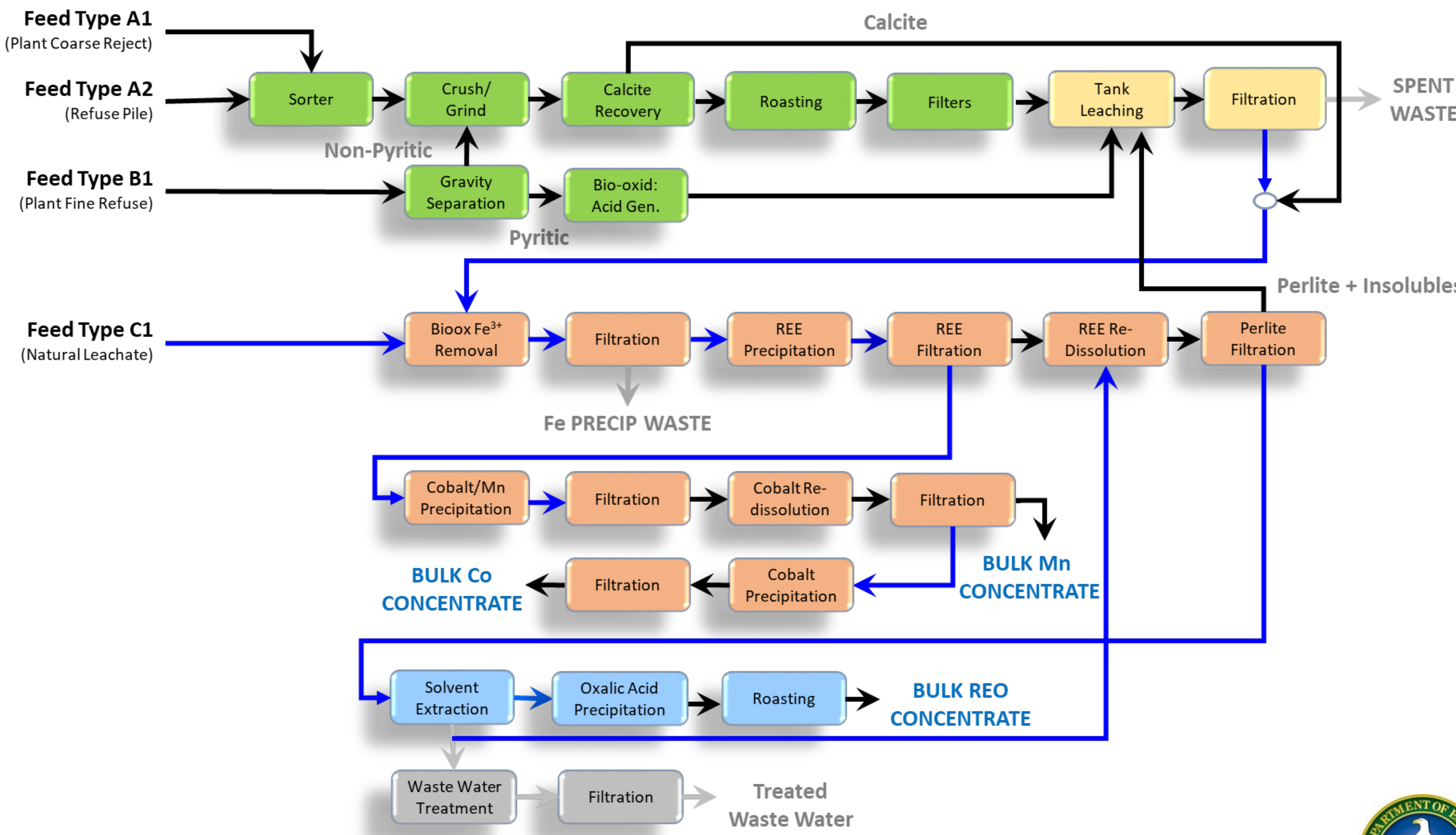
Size Fraction (mesh)	Weight (%)	Major Minerals (%)			
		Pyrite	Silica	Calcite	Kaolinite
+100	8.84	6.3	6.4	68.2	4.9
100 x 200	43.72	20.0	14.1	62.8	3.1
200 x 325	14.88	43.3	12.2	35.4	1.1
-325	32.56	30.1	44.8	21.0	3.7
Total	**100.00**	**25.5**	**23.1**	**45.6**	**3.2**

PROJECT DISCUSSION: SULFURIC ACID PRODUCTION

- Concentrated pyrite is used as feed to a bio-oxidation reactor.
- Bacteria is used to drive the oxidation reaction converting Fe^{2+} to Fe^{3+}.
- Tests have indicated that 0.2M sulfuric acid can be consistently produced with a pH value around 1.0 – 1.2.
- Acid cost reduction is anticipated to be 75% or greater.



PROJECT DISCUSSION: PROCESS BLOCK DIAGRAM



PROJECT DISCUSSION: PILOT PLANT

PROJECT DISCUSSION: PRODUCTS GENERATED TO DATE

Test No.	Sample Source	Percent Concentration (%)																
		Sc	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Total REO
1	WK 13 Acid Drainage	0.00	36.44	0.55	7.80	4.15	10.01	7.11	2.24	11.54	1.94	9.24	1.52	3.06	0.17	0.66	0.06	96.48
2	WK 13 Coarse Refuse	0.05	2.27	12.22	31.73	4.24	15.45	2.78	0.44	1.55	0.00	0.58	0.10	0.27	0.00	0.14	0.02	71.83
4	WK 13 Coarse Refuse	0.04	2.73	16.81	44.08	4.36	15.39	2.34	0.38	1.58	0.00	0.90	0.52	0.24	0.23	0.17	0.07	89.86
5	WK 13 Coarse Refuse	0.02	3.60	14.96	43.61	4.63	17.42	3.01	0.48	2.29	0.00	1.25	0.55	0.30	0.23	0.19	0.06	92.61
7	WK 13 Coarse Refuse	0.02	3.37	17.78	45.01	4.44	15.78	2.47	0.41	1.89	0.00	1.04	0.57	0.28	0.24	0.19	0.07	93.57
4	Fire Clay Coarse Refuse	0.01	3.99	15.00	45.02	4.87	16.87	3.79	0.47	2.31	0.00	1.54	0.22	0.29	0.04	0.21	0.08	94.68
5	Fire Clay Coarse Refuse	0.01	3.72	11.85	43.46	4.54	16.15	3.38	0.50	2.43	0.00	1.42	0.41	0.29	0.04	0.24	0.09	88.52
6	Fire Clay Coarse Refuse	0.00	3.32	15.61	43.32	4.43	15.45	2.57	0.41	1.87	0.00	1.27	0.49	0.28	0.04	0.20	0.08	89.34

Test No.	Sample Source	Percent Concentration (%)																
		Sc	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Total REO
4	Fire Clay Coarse Refuse	0.01	3.99	15.00	45.02	4.87	16.87	3.79	0.47	2.31	0.00	1.54	0.22	0.29	0.04	0.21	0.08	94.68
5	Fire Clay Coarse Refuse	0.01	3.72	11.85	43.46	4.54	16.15	3.38	0.50	2.43	0.00	1.42	0.41	0.29	0.04	0.24	0.09	88.52
6	Fire Clay Coarse Refuse	0.00	3.32	15.61	43.32	4.43	15.45	2.57	0.41	1.87	0.00	1.27	0.49	0.28	0.04	0.20	0.08	89.34

ENVIRONMENTAL IMPACTS

Mine Waste Remediation:

- AMD prevention by recovering pyritic material from the solid waste.
- Solidify and immobilize metal ions.
- Solid waste consolidation for centralized management.

Bio-leach Process:

- Eliminate potential hazard of sulfur dioxide emission in conventional contact process to produce sulfuric acid.
- Avoid transportation and storage of high concentration sulfuric acid.
- Improve worker safety.

Indirect Impact:

- Reduce requirement for caustic chemical production by using caustic material recovered from the mine waste.

PERMITTING PROJECTS

For the pilot plant, a Coal Exploration permit (Notice 117-E186) was required by the Kentucky Department of Environmental Protection.

All pilot plant solid and water wastes are transported to an MSHA permitted coarse coal waste facility.

Thorium and uranium recoveries from the solids are low.

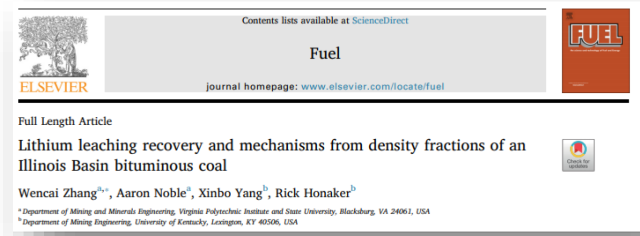
Commercial permitting requirements will be subject to an exemption ruling under SMCRA: New Mine Permit (long-term process) or as a non-coal operation (short-term process).

Rapid TRL Advancement is anticipated with the current process flowsheet.

- The process is being implemented into an existing pilot facility, which can serve as a testbed for future technology developments.
- During the initial development of the pilot plant, the team advanced from a white page process design to a pilot process within 2.5 years.
- Many unit operations are mature technologies where scaling relationships are well known.

Ongoing research is also addressing the synergistic production of Non-REE critical elements, such as Li, Mn, Sr, V, Co, and Cr.

Non-REE Critical Minerals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Full Length Article

Lithium leaching recovery and mechanisms from density fractions of an Illinois Basin bituminous coal

Wencai Zhang[a,*], Aaron Noble[a], Xinbo Yang[b], Rick Honaker[b]

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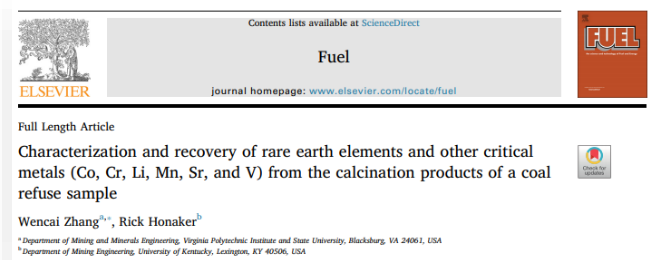
[b] Department of Mining Engineering, University of Kentucky, Lexington, KY 40506, USA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ELSEVIER

Full Length Article

Characterization and recovery of rare earth elements and other critical metals (Co, Cr, Li, Mn, Sr, and V) from the calcination products of a coal refuse sample

Wencai Zhang[a,*], Rick Honaker[b]

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[b] Department of Mining Engineering, University of Kentucky, Lexington, KY 40506, USA

COMMERCIALIZATION ISSUES

Needs:

- Elemental Separations
- Downstream refining
- Sales/Offtake Agreements

Opportunities/Strengths:

- No Mining Cost
- Existing Workforce
- Academic knowledge-base for technical training

Lynas Mt. Weld REE Concentration Plant

Northern Minerals Heavy REE Pilot Plant