Extraction and Recovery of Rare Earth Elements from Coal and Coal Byproducts

Virginia Coal and Energy Alliance, Inc.
2018 PE Seminar Program

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Virginia Tech
Acknowledgement & Disclaimer

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- All the students, post-docs, technicians, plant personnel, and other researchers who have contributed to this work.

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Presentation Outline

1. Background
2. Rare Earths in Coal
3. Liberation of REEs
4. Concluding Remarks
What Are Rare Earths?
What are Rare Earths?

**Rare Earth Elements**

<table>
<thead>
<tr>
<th></th>
<th>Ce</th>
<th>Pr</th>
<th>Nd</th>
<th>Pm*</th>
<th>Sm</th>
<th>Eu</th>
<th>Gd</th>
<th>Tb</th>
<th>Dy</th>
<th>Ho</th>
<th>Er</th>
<th>Tm</th>
<th>Yb</th>
<th>Lu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th</td>
<td>Pa</td>
<td>U</td>
<td>Np</td>
<td>Pt</td>
<td>Am</td>
<td>Cm</td>
<td>Bk</td>
<td>Cf</td>
<td>Es</td>
<td>Fm</td>
<td>Md</td>
<td>No</td>
<td>Lr</td>
<td></td>
</tr>
</tbody>
</table>

**Critical**

*Unstable*

Lanthanum: Greek *Lanthanein* = to escape notice

Dysprosium: Greek *Dysprositos* = hard to get
What are Rare Earths?

- LCD screen
  - Europium
  - Yttrium
  - Cerium

- Glass and mirrors polishing powder
  - Cerium

- Component sensors
  - Yttrium

- UV cut glass
  - Cerium

- Diesel fuel additive
  - Cerium
  - Lanthanum

- Hybrid electric motor and generator
  - Neodymium
  - Praseodymium
  - Dysprosium
  - Terbium

- Headlight glass
  - Neodymium

- 25+ electric motors throughout vehicle
  - Neodymium magnets

- Hybrid NiMH battery
  - Lanthanum
  - Cerium

- Catalytic converter
  - Cerium
  - Lanthanum
What are Rare Earths?

Distribution of REE According to End Use

- Glass Industry: 22%
- Catalysts: 21%
- Magnets: 20%
- Battery Alloys: 9%
- Metallurgy: 9%
- Phosphor: 7%
- Ceramics: 6%
- Other: 6%

Source: USGS Rare Earth Elements – End use and Recyclability, 2011
REE's Aren't “Rare”

ABUNDANCE OF ELEMENTS

- Rock-forming elements (major elements in green field and minor elements in light green field)
- Major industrial metals (global production $>3 \times 10^7$ kg/year)
- Precious metals
- Rare earth elements (lanthanides, Sc, and Y)

Source: USGS, Fact Sheet 087-02
Nearly all critical materials for energy are REE

Source: US DOE, Critical Materials Strategy
US Import Reliance

100% import reliance on REEs

Bayan Obo Iron Ore Mine
Chief REE Resources

Mineral Phase Resources

- Monazite
- Bastnäsite
- Zenotime

Other Resources

- Ion Substituted Clay

Chinese REE Production Forecast

REE Mining and Processing

Generalized flowsheet for hard rock processing

Source: British Geologic Survey, Rare Earth Elements, 2011
Current Rare Earth Projects

Source: Szumigla and Werdon, State of Alaska, Department of Natural Resources, Information Circular 61
Rare Earths in Coal?
Prophesy

“By the year 2000, we will not be wasting our coal ash, in which geochemists have shown that there is a notable concentration of rare elements, such as germanium and rare earths. We will be recovering these elements.”

Dr. Edward Steidle
Mineral Forecast 2000 AD (1952)
The Pennsylvania State College
Rare Earths in Coal/Coal Ash

REE Concentrations > 1000 ppm (ash basis)

Areas outlined in yellow were the focus of further analysis.

Source: Ekmann, 2012
US REO Consumption = 15,000 to 17,000 tpy (USGS/Gambogi)
Resource Size

Number of Coal Preparation Facilities per State

Source: Steve Fiscor || Coal Age || October, 2016

Total = 252 Plants in 12 States (>200,000 TPH of installed capacity)
Coal-Based REE Resources

**Combustion Byproducts**

- **Advantages**
  - Preliminary Upgrading
  - REE: 400 to 1200 PPM
  - Waste utilization

- **Challenges**
  - Glass encapsulation
  - Difficult to Process

**Mining/Prep Plant Products**

- **Advantages**
  - “Natural” REE phases
  - Moderate processing
  - Potential for additional material recovery

- **Challenges**
  - Low Grades
  - REE: 250 to 450 PPM

**Aqueous Effluents**

- **Advantages**
  - Natural Upgrading
  - REE: 550 to 1500 PPM
  - Easy to process

- **Challenges**
  - Low Volume
  - Relatively small reserves
Potential Recovery Flowsheet

Is it possible to construct this plant with current technology?
Economic Evaluation

**Current REE Oxide Prices**

<table>
<thead>
<tr>
<th>Element</th>
<th>Value (US $/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sc</td>
<td>$2,000</td>
</tr>
<tr>
<td>Y</td>
<td>$3.30</td>
</tr>
<tr>
<td>La</td>
<td>$2.30</td>
</tr>
<tr>
<td>Ce</td>
<td>$2.30</td>
</tr>
<tr>
<td>Pr</td>
<td>$72.50</td>
</tr>
<tr>
<td>Nd</td>
<td>$64.50</td>
</tr>
<tr>
<td>Sm</td>
<td>$1.90</td>
</tr>
<tr>
<td>Eu</td>
<td>$71.00</td>
</tr>
<tr>
<td>Gd</td>
<td>$19.50</td>
</tr>
<tr>
<td>Tb</td>
<td>$600.00</td>
</tr>
<tr>
<td>Dy</td>
<td>$180.00</td>
</tr>
<tr>
<td>Ho</td>
<td>--</td>
</tr>
<tr>
<td>Er</td>
<td>$26.70</td>
</tr>
<tr>
<td>Tm</td>
<td>--</td>
</tr>
<tr>
<td>Yb</td>
<td>--</td>
</tr>
<tr>
<td>Lu</td>
<td>--</td>
</tr>
</tbody>
</table>

**REE Value in Individual Stream ($/ton)**

- **Current Market Values**
  - Optimistic Values: $604 - $778 / kg REE (Max of 2008 to 2017 by element)
  - Pessimistic Values: $126 - $182 / kg REE (Min of 2008 to 2017 by element)

- **Current Realisable Values**
  - Optimistic Values: $604 - $778 / kg REE (Max of 2008 to 2017 by element)
  - Pessimistic Values: $126 - $182 / kg REE (Min of 2008 to 2017 by element)

- **Reject/Rock (>30% Ash)**

- **Coal (<30% Ash)**
Channel Sample (NAPP)

Nominal REE Value per Ton of Strata

REE Value in Individual Strata ($/ton)

- B1-Shale
- B2-Coal
- B3-Carb. Shale
- B4-Fireclay
- B5-Fireclay
- B6-Shale
- B7-Carb. Shale
- B8-Coal
- B9-Coal
- B10-Bone
- B11-Coal
- B12-Coal
- B13-Fireclay
Contained Value

Nominal REE Value per Ton of Material

Site A, Fine Refuse
Site A, Middlings
Site A, Coarse Refuse
Site B, Fine Refuse
Site B, Coarse Refuse
Site C, Fine Refuse
Tantalus Project

$/tonne of Feed

Advanced REE development project in Madagascar
Liberation and Release of REEs
Potential Recovery Flowsheet

REE Supply Chain

Prep Plant

Waste

REE Recovery Plant

REE Recovery Plant

REE Recovery Plant

REE Supply Chain

REE Recovery Plant

REE Recovery Plant

REE Recovery Plant

REE Recovery Plant

Crushing and Grinding

Physical Separations

Hydrometallurgy

Other Valuable Products

REE Product

REE Product

REE Product

REE Product

REE Product
SEM/EDX Analysis
SEM/EDX Analysis

Objects 206

SE MAG: 7917 x  HV: 20.0 kV  WD: 11.5 mm  Px: 20 nm

image 19

11/29/2017 10:52:34 AM  HV 20.00 kV  mag 1.177 x  WD 11.5 mm  spot 4.0  det BSED  hH_17P-Ti1-Sn20
SEM/EDX Analysis

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>C</th>
<th>O</th>
<th>Al</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
<th>La</th>
<th>Ce</th>
<th>Pt</th>
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<tbody>
<tr>
<td>BHEM Rougher Conc n1 1</td>
<td>75.06</td>
<td>4.41</td>
<td>4.20</td>
<td>10.45</td>
<td>-</td>
<td>-</td>
<td>1.94</td>
<td>3.93</td>
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<td>BHEM Rougher Conc n1 2</td>
<td>66.40</td>
<td>-</td>
<td>0.81</td>
<td>1.08</td>
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<td>18.82</td>
<td>12.60</td>
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<td>BHEM Rougher Conc n1 3</td>
<td>74.29</td>
<td>10.25</td>
<td>0.17</td>
<td>0.19</td>
<td>-</td>
<td>8.76</td>
<td>6.33</td>
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<td>BHEM Rougher Conc n1 4</td>
<td>52.28</td>
<td>17.70</td>
<td>0.99</td>
<td>0.87</td>
<td>-</td>
<td>17.64</td>
<td>10.32</td>
<td>-</td>
<td>-</td>
<td>0.20</td>
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<tr>
<td>Mean value:</td>
<td>64.32</td>
<td>34.34</td>
<td>1.60</td>
<td>1.59</td>
<td>10.45</td>
<td>15.08</td>
<td>9.75</td>
<td>1.94</td>
<td>3.93</td>
<td>0.24</td>
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<tr>
<td>Sigma:</td>
<td>11.15</td>
<td>35.46</td>
<td>1.91</td>
<td>1.79</td>
<td>0.00</td>
<td>5.50</td>
<td>3.17</td>
<td>0.00</td>
<td>0.00</td>
<td>0.06</td>
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<tr>
<td>Sigma mean:</td>
<td>5.58</td>
<td>17.73</td>
<td>0.96</td>
<td>0.89</td>
<td>0.00</td>
<td>2.75</td>
<td>1.59</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
</tr>
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</table>
Progressive REE Release Tests

Middlings Coal
SG = 1.4 x 2
REE = 100 – 350 PPM

Grind for 1 to 12 minutes
Screen at 250 μm
Float to Recovery Coal

Low Ash Coal
High Ash Tailings

REE Analysis

Grind Product Size, P80 (microns)

REE in Tailings (PPM)

- Fire Clay
- West KY #13
- Middle Kittanning

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REE vs. Ash (All Samples)

![Graph showing the relationship between REE Content, WC (PPM) and Ash Content (%)]

- Fire Clay
- West KY #13
- Middle Kittanning

Questions:
- Pure Ash Composition?
- Inherent Organic Affinity?
REE vs. Ash (All Samples)

- Fire Clay
- West KY #13
- Middle Kittanning

**Pure Ash Composition?**

REE Content, WC (PPM)

Ash Content (%)

Inherent Organic Affinity?

**Powder Technology**
Available online 26 March 2018
In Press, Accepted Manuscript — Note to users

Liberation and release of rare earth minerals from middling Kittanning, fire clay, and West Kentucky no. 13 coal sources

Qingqing Huang’a, Aaron Nobleb, John Herbst’a, Rick Honaker²

https://doi.org/10.1016/j.powtec.2018.03.063
Summary and Conclusions
Summary

The REE resource contained in US coal and coal byproducts have sufficient to support most if not all of US demand.

To convert that resource into a reserve, several DOE-funded projects are developing advanced separation technologies.

These technologies will soon be tested at the pilot scale.
Questions?

- [https://www.netl.doe.gov/research/coal/rare-earth-elements](https://www.netl.doe.gov/research/coal/rare-earth-elements)
- [https://edx.netl.doe.gov/ree/](https://edx.netl.doe.gov/ree/)
Questions?

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