BUILDING A NEW ASSESSMENT TOOL FOR POTENTIAL RARE EARTH UNDERGROUND MINING PROJECTS

SDIMI 2015
Vancouver, Canada

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Helmut MISCHO
Scope of Research

Special Evaluations in Rare Earth Mining

Traditional Evaluation Methods

REE-Mining Industry Specific Criteria

Numerical Methods & Techniques in the Assessment Tool

Structure of the Assessment Tool for Rare Earth Underground Mining Projects
Special Evaluations in Rare Earth Mining

What makes rare earth mining so special?

- Fragile market
- The Balance Problem
- Legislation
- Difficulties in processing
- Radioactivity
- Tailings

- Environmental issues
- Lack of proper knowledge & experience
- Social arguments

(Source: www.adn.com)
Traditional Evaluation Methods

- Boshkov & Wright (1973)
- Morrison (1976)
- Laubscher (1981)
- Nicholas (1981)
- Hartman (1987)
- UBC (1995)
- ...
- AHP
- ANP
- PROMETHEE
- Fuzzy logic techniques
- Trapezoidal fuzzy numbers

What determines the type of mining?

Lower Cost
Maximum Profit

Rock Mass Properties
Shape, Geometry & Position of Deposit
REE-Mining Industry Specific Criteria

The triple-bottom-line (TBL)
The three pillars of sustainability

- Geological
- Technical
- ...
- Economic
- Environmental
- Sociopolitical

Need for a detailed evaluation tool focused on the viability of REE projects
REE-Mining Industry Specific Criteria

Evaluation Criteria for REE mining

Spatial characteristics of deposit
- Size
- Shape
- Attitude
- Depth
- Regularity of ore boundaries
- Existence of previous mining

Geologic & hydrologic conditions
- Mineralogy, petrography
- Chemical composition
- Deposit structure
- Planes of weakness
- Uniformity of grade
- Alternation, weathered zones
- Existence & mobility of strata gases
- Occurrence of radioactivity

Geotechnical properties
- Elastic properties
- Plastic or viscoelastic behavior
- State of stress
- Stability & rock mass rating
- Other physical properties

Technological factors
- Recovery
- Dilution
- Flexibility of method to changing
- Selectivity of method
- Concentration or dispersion
- Ability to mechanize & automate
- Capital & labor costs

Health & Safety
- Minimization of dust production
- Mobilization of radiation
- Atmospheric control & ventilation

Environmental concerns
- Ground control
- Subsidence or caving effects
- Waste disposal & backfilling
- Comparative safety conditions
- Water treatment

Sociopolitical considerations
- Intellectual capital
- Legislation & environmental regulations
- Processing plant licenses
- Political stability
- Social arguments
- Availability of workforce

Economic considerations
- Reserves
- Production rate
- Mine life
- Productivity
- Comparative mining costs
- Comparative capital costs
- Balance of REEs
- Current & future prices predictions
- By products

(Source: Barakos & Mischo, 2015; modified after Hartman & Mutmansky, 2002)
Numerical Methods & Techniques in the Assessment Tool

- Analytical Hierarchical Process (AHP)

- Numerical approach for evaluation (Nicholas method)

- Sensitivity analysis model
The Analytical Hierarchical Process

- Multi-criteria decision process
- Subdivision of problems in an hierarchical form
- Pair-wise comparison of components
- Prioritization of criteria by setting weight factors on them

<table>
<thead>
<tr>
<th>Relative Intensity</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Of equal value</td>
<td>Two elements are of equal value</td>
</tr>
<tr>
<td>3</td>
<td>Slightly more</td>
<td>Experience slightly favors one element over another</td>
</tr>
<tr>
<td></td>
<td>value</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Essential or</td>
<td>Experience strongly favors one element over another</td>
</tr>
<tr>
<td></td>
<td>strong value</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Very strong</td>
<td>An element is strongly favored and its dominance is demonstrated in practice</td>
</tr>
<tr>
<td></td>
<td>value</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Extreme value</td>
<td>The evidence favoring one over another is of the highest order of affirmation</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate</td>
<td>When compromise is needed</td>
</tr>
<tr>
<td></td>
<td>values</td>
<td></td>
</tr>
</tbody>
</table>
The Analytical Hierarchical Process

Pair-wise comparison over $n$ criteria

$$A = \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix}, \quad a_{ii} = 1, \quad a_{ji} = \frac{1}{a_{ij}}, a_{ij} \neq 0$$

Computing the vector of weights

$$a_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad \Rightarrow \quad w_i = \frac{\sum_{i=1}^{n} a_{ij}}{n}$$

Consistency of comparisons

$$CI = \frac{\lambda_{\text{max}} - n}{(n-1)}$$

$$CR = \frac{CI}{RI}$$
Numerical Approach for Evaluation (Based on Nicholas)

• Ranking values for the suitability of a mining method to each criterion

• Intermediate values can be given for greater accuracy

• Many parameters are already quantified in classification schemes

• Evaluation of non-quantified criteria is based on experience and past cases

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongly preferred</td>
<td>5</td>
</tr>
<tr>
<td>Slightly preferred</td>
<td>3-4</td>
</tr>
<tr>
<td>Probable</td>
<td>1-2</td>
</tr>
<tr>
<td>Unlikely</td>
<td>0</td>
</tr>
<tr>
<td>Eliminated</td>
<td>-49</td>
</tr>
</tbody>
</table>

(Source: modified after Nicholas, 1981)
# Numerical Approach for Evaluation (Based on Nicholas)

## Definition of deposit geometry and grade distribution

<table>
<thead>
<tr>
<th>General shape/width</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equidimensional</td>
<td>All dimensions are on same order of magnitude.</td>
</tr>
<tr>
<td>Platy-tabular</td>
<td>Two dimensions are many times the thickness, which does not usually exceed 100 m.</td>
</tr>
<tr>
<td>Irregular</td>
<td>Dimensions vary over short distances.</td>
</tr>
</tbody>
</table>

### Ore thickness

<table>
<thead>
<tr>
<th>Type</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>&lt;10 m</td>
</tr>
<tr>
<td>Intermediate</td>
<td>10–30 m</td>
</tr>
<tr>
<td>Thick</td>
<td>30–100 m</td>
</tr>
<tr>
<td>Very thick</td>
<td>&gt;100 m</td>
</tr>
</tbody>
</table>

### Plunge

<table>
<thead>
<tr>
<th>Type</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>&lt;20°</td>
</tr>
<tr>
<td>Intermediate</td>
<td>20°–55°</td>
</tr>
<tr>
<td>Steep</td>
<td>&gt;55°</td>
</tr>
</tbody>
</table>

### Depth below surface

<table>
<thead>
<tr>
<th>Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Provide actual depth.</td>
</tr>
</tbody>
</table>

### Grade distribution

<table>
<thead>
<tr>
<th>Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform</td>
<td>Grade at any point in deposit does not vary significantly from mean grade for that deposit.</td>
</tr>
<tr>
<td>Gradational</td>
<td>Grade values have zonal characteristics, and the grades change gradually from one to another.</td>
</tr>
<tr>
<td>Erratic</td>
<td>Grade values change radically over short distances and do not exhibit any discernible pattern in their changes.</td>
</tr>
</tbody>
</table>

## Rock mechanics characteristics

### Rock Substance Strength (uniaxial strength/overburden pressure)

<table>
<thead>
<tr>
<th>Strength</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>&lt;8</td>
</tr>
<tr>
<td>Moderate</td>
<td>8–15</td>
</tr>
<tr>
<td>Strong</td>
<td>&gt;15</td>
</tr>
</tbody>
</table>

### Fracture Frequency

<table>
<thead>
<tr>
<th>Fracture Frequency</th>
<th>No. of Fractures/m</th>
<th>% RQD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very close</td>
<td>&gt;16</td>
<td>0–20</td>
</tr>
<tr>
<td>Close</td>
<td>10–16</td>
<td>20–40</td>
</tr>
<tr>
<td>Wide</td>
<td>3–10</td>
<td>40–70</td>
</tr>
<tr>
<td>Very wide</td>
<td>&lt;3</td>
<td>70–100</td>
</tr>
</tbody>
</table>

### Fracture Shear Strength

<table>
<thead>
<tr>
<th>Strength</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>Clean joint with smooth surface or fill with material with strength less than rock substance strength</td>
</tr>
<tr>
<td>Moderate</td>
<td>Clean joint with rough surface</td>
</tr>
<tr>
<td>Strong</td>
<td>Joint filled with material that is equal to or stronger than rock substance strength</td>
</tr>
</tbody>
</table>

(Source: Nicholas, 1992)
The Sensitivity Analysis Model

- “Subjective” decisions in the selection process
- Most critical criteria have the highest weight factors (?)

**Sensitivity Analysis Model on Weights**

- Smallest change on weights that can influence the ranking of mining methods

Variation of one single value at a time

Change two or more parameters simultaneously
Structure of the Assessment Tool

- Quantification and assessment of all possible factors
- Critical ability using quantified data and experience
- AHP and weight factors
- Re-evaluation loops
- Sensitivity Analysis
## Classification of Mining Methods

<table>
<thead>
<tr>
<th>Locale</th>
<th>Class</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>Mechanical</td>
<td>Open pit mining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quarrying</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Open cast (strip) mining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Auger mining</td>
</tr>
<tr>
<td></td>
<td>Aqueous</td>
<td>Hydraulicking</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dredging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Borehole mining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leaching</td>
</tr>
<tr>
<td>Underground</td>
<td>Unsupported</td>
<td>Room-and-pillar mining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stope-and-pillar mining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shrinkage stoping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sublevel stoping</td>
</tr>
<tr>
<td></td>
<td>Supported</td>
<td>Cut-and-fill stoping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stull stoping</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Square-set stoping</td>
</tr>
<tr>
<td></td>
<td>Caving</td>
<td>Longwall mining</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sublevel caving</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Block caving</td>
</tr>
</tbody>
</table>

(Source: modified after Hartman & Mutmansky, 2002)
Structure of the Assessment Tool

1st Evaluation Stage

1st Stage

Start of evaluation

- Set the categories and criteria

Evaluation of some basic criteria:

- Geographic conditions (location, social)
- Infrastructure
- Mineralogy, grade, REE-type
- Metallurgical tests, recovery
- Legislation, licenses

Ensure that the REE project has potentials

2nd Stage

Early evaluation stage of criteria
- In this stage we examine the criteria in the first 3 categories
  i) Spatial characteristics of deposit
  ii) Geologic-hydrologic conditions
  iii) Geotechnical properties
- AHP for weighted criteria
- Ranking of mining methods
- Surface/underground mining
- Elimination of unsuitable mining methods to reduce
- Scores of qualifying methods are transferred to next stage

3rd Stage

Main evaluation stage of criteria
- In this stage we examine the criteria in the categories 4-8
  iv) Economic considerations
  v) Technological factors
  vi) Environmental concerns
  vii) Sociopolitical considerations
  viii) Health & safety concerns
- AHP for weighted criteria
- Ranking of mining methods
- Sensitivity analysis for criteria

4th Stage

Conclude to 2-3 most suitable methods;
- Prefeasibility studies for all environmental studies of them

Final decision on the method
- Feasibility study
- Decision on investment

NEPA and permitting
Financing

END OF EVALUATION
START OF PROJECT
Structure of the Assessment Tool

2\textsuperscript{nd} Evaluation Stage

2\textsuperscript{nd} Stage

Early evaluation of criteria

- Examination of the criteria in the first 3 categories
  
i) spatial characteristics of deposit
  
ii) geologic-hydrologic conditions
  
iii) geotechnical properties

-AHP for weighted criteria

-Ranking of mining methods

-Surface/underground mining

-Elimination of unsuitable mining methods

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Yes

No

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START OF PROJECT
Structure of the Assessment Tool
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Structure of the Assessment Tool

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Yes
Ne

NEPA and permitting
Financing

END OF EVALUATION
START OF PROJECT
Conclusions and Perspectives

• An approach to create an integrated evaluation process
• The tool is applicable to other kind of deposits

• Weight factors calculated with Analytical Hierarchical Process
• Ranking of mining methods with the “Nicholas” ranking system

• No active REE underground mines to derive data, knowledge, experience
• Next step is to investigate interesting REE potential projects

• The goal is to check the functionality and consistence of the tool
• Optimization of evaluation process
• Combination of the theoretical tool with mine planning design software
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THANK YOU FOR YOUR ATTENTION

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