



# NETL Life Cycle Inventory Data

## Process Documentation File

**Process Name:** Rare earth leaching  
**Reference Flow:** 1 kg of rare earth chloride concentrate  
**Brief Description:** The leaching of rare earth concentrate

### Section I: Meta Data

**Geographical Coverage:** N/A **Region:** N/A  
**Year Data Best Represents:** N/A  
**Process Type:** Manufacturing Process (MP)  
**Process Scope:** Gate-to-Gate Process (GG)  
**Allocation Applied:** No  
**Completeness:** Individual Relevant Flows Captured

**Flows Aggregated in Data Set:**

- Process
         
  Energy Use
         
  Energy P&D
         
  Material P&D

**Relevant Output Flows Included in Data Set:**

- Releases to Air:
     
  Greenhouse Gases
     
  Criteria Air
     
  Other
- Releases to Water:
     
  Inorganic
     
  Organic Emissions
     
  Other
- Water Usage:
     
  Water Consumption
     
  Water Demand (throughput)
- Releases to Soil:
     
  Inorganic Releases
     
  Organic Releases
     
  Other

**Adjustable Process Parameters:**

- hcl\_leach                      *[binary] Leach with hydrochloric acid*
- h2so4\_leach                    *[binary] Leach with sulfuric acid*
- naoh\_leach                     *[binary] Leach with caustic soda*
- bastnaesite                    *[binary] Bastnaesite ore is input*
- monazite                        *[binary] Monazite/xenotime ore is input*
- U\_ins                            *[J/s-m<sup>2</sup>-K] Heat transfer coefficient (used to estimate heat loss), default assumes 6-inch thick firebrick*

ore_frac_reo	<i>[kg/kg] kg of REO equivalent per kg of rare earth concentrate input</i>
RE_ore_conv	<i>[kg/kg] kg of bastnaesite per kg of REO equivalent (site-specific)</i>
mol_wt_re	<i>[kg/mol] Molecular weight of the rare earth element mix in rare earth containing mineral (default mountain pass bastnaesite)</i>

**Tracked Input Flows:**

rare earth ore concentrate	<i>Reference flow - ore input for the leaching process (from beneficiation)</i>
Heat, from Mountain Pass CHP	<i>[Technosphere] heat input for the leaching process</i>
Hydrochloric acid (100%)	<i>[Technosphere] hydrochloric acid</i>
Sulphuric acid aq. (96%)	<i>[Technosphere] sulfuric acid</i>
Sodium hydroxide (100%; caustic soda)	<i>[Technosphere] sodium hydroxide acid</i>
Water	<i>[Resource] Water</i>
Sodium chloride	<i>[Technosphere] Salt</i>

**Tracked Output Flows:**

rare earth chloride concentrate	<i>[Technosphere] Mixed rare earth chlorides in aqueous phase</i>
Carbon dioxide	<i>Emissions to air</i>
Hydrogen fluoride	<i>Emissions to air</i>
Phosphoric acid waste	<i>Dilute phosphoric acid solution waste solution</i>
solid waste	<i>Solid waste (gangue material)</i>
dilute acid waste	<i>Acid waste (mix of HCl, water, and sodium sulfate)</i>
Trisodium phosphate waste	<i>Dilute trisodium phosphate waste</i>
sodium fluoride	<i>Sodium fluoride</i>

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**Section II: Process Description**


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**Associated Documentation**

This unit process is composed of this document and the data sheet (DS) *DS\_Stage1\_O\_Rare\_Earth\_Leaching\_2014.01.xlsx*, which provides additional details regarding relevant calculations, data quality, and references.

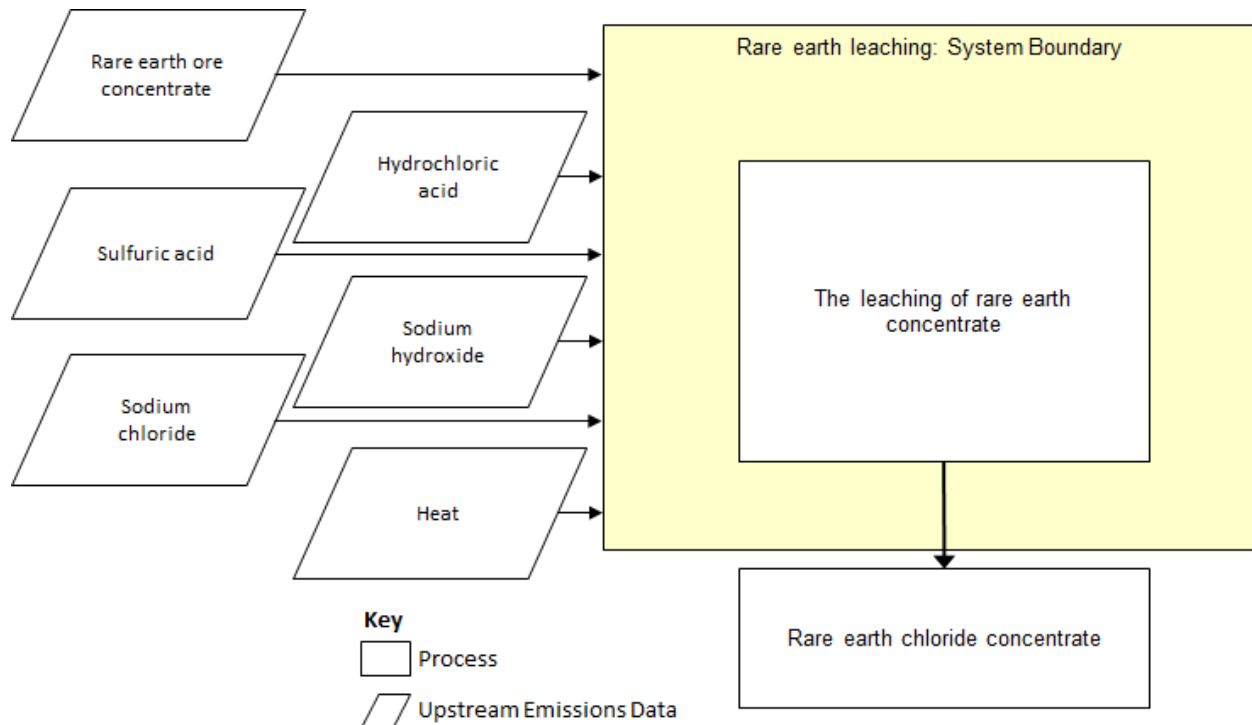
### Goal and Scope

This unit process provides a summary of relevant input and output flows associated with leaching rare earth concentrate with strong acids or bases to produce an aqueous solution. Inputs include process heat and either hydrochloric acid, sulfuric acid, or caustic soda. The output is an aqueous phase mix of rare earth chlorides. The reference flow of this unit process is: 1 kg of rare earth chloride concentrate.

### Boundary and Description

**Figure 1** provides an overview of the boundary of this unit process. Rectangular boxes represent relevant sub-processes, while trapezoidal boxes indicate upstream data that are outside of the boundary of this unit process. As shown, the upstream emissions from hydrochloric and sulfuric acid, caustic soda, salt, and rare earth concentrate are calculated other unit processes. The methods for calculating these operating activities are described below.

**Figure 1: Unit Process Scope and Boundary**



The process allows the input of rare earth concentrate made up of either bastnaesite or monazite/xenotime, mineral ores that contain rare earth elements. This selection is

performed using the binary parameters *bastnaesite* and *monazite*. Due to limited data availability, each mineral cannot be used with the three different types of solvents. Bastnaesite can only be leached with hydrochloric acid or sulfuric acid in this unit process. Monazite/xenotime can only be leached with sulfuric acid or caustic soda. Binary parameters control the choice of solvent to be used and can allow any combination of minerals and solvents, so care must be taken to make the appropriate choices. The combination of mineral and solvent automatically change the temperature of the leaching bath.

In addition to choosing the appropriate mineral/solvent combination, the user must provide properties that are specific to the concentrate and mineral being used. The first is the total rare earth oxide (TREO) equivalent fraction of rare earth concentrate, *ore\_frac\_reo*. Rare earth minerals and intermediate process flows are commonly rated according to the amount of rare earth oxides that could be made if the rare earth elements contained in the minerals are converted to their commonly used oxide. Therefore TREO doesn't represent the fraction of the rare earth ore concentrate that is bastnaesite or monazite/xenotime. To convert the REO fraction to mineral content, a second parameter is used, *RE\_ore\_conv*, which represents the conversion of the rare earth elements to the appropriate mineral (e.g., Ce from CeO<sub>2</sub> converted to CeFCO<sub>3</sub> – bastnaesite or CePO<sub>4</sub> – monazite). This DS documents the conversion for Mountain Pass bastnaesite. **Table 1** and **Table 2** provide the typical fractions of REO content for bastnaesite from Mountain Pass and monazite from the Guangdong region of China. The last parameter is the molar mass of the mix of rare earth elements, *mol\_wt\_re*, calculated by converting the TREO content into moles of rare earth elements. The moles for the individual elements are multiplied by the molar mass to convert the molar amounts to mass. The total mass for the mix is divided by the total moles for the mix for the *mol\_wt\_re* parameter. These parameters are used to calculate the stoichiometric amount of solvent and other materials required for each of the scenarios.

**Table 1: Bastnaesite REO and mineral composition**

Rare Earth Oxide	Fraction of Bastnaesite Rare Earth Oxide Content (kg/kg TREO) (Gupta and Krishnamurthy, 2005)	Bastnaesite Component	Fraction of bastnaesite (kg bastnaesite/kg TREO)
CeO <sub>2</sub>	4.91E-01	CeFCO <sub>3</sub>	6.25E-01
La <sub>2</sub> O <sub>3</sub>	3.32E-01	LaFCO <sub>3</sub>	4.44E-01
Pr <sub>6</sub> O <sub>11</sub>	4.34E-02	PrFCO <sub>3</sub>	5.61E-02
Nd <sub>2</sub> O <sub>3</sub>	1.20E-01	NdFCO <sub>3</sub>	1.59E-01
Sm <sub>2</sub> O <sub>3</sub>	7.89E-03	SmFCO <sub>3</sub>	1.04E-02
Eu <sub>2</sub> O <sub>3</sub>	1.18E-03	EuFCO <sub>3</sub>	1.55E-03
Gd <sub>2</sub> O <sub>3</sub>	1.66E-03	GdFCO <sub>3</sub>	2.16E-03
Tb <sub>4</sub> O <sub>7</sub>	1.59E-04	TbFCO <sub>3</sub>	2.02E-04

Dy <sub>2</sub> O <sub>3</sub>	3.12E-04	DyFCO <sub>3</sub>	4.04E-04
Ho <sub>2</sub> O <sub>3</sub>	5.10E-05	HoFCO <sub>3</sub>	6.58E-05
Er <sub>2</sub> O <sub>3</sub>	3.50E-05	ErFCO <sub>3</sub>	4.51E-05
Tm <sub>2</sub> O <sub>3</sub>	9.00E-06	TmFCO <sub>3</sub>	1.16E-05
Yb <sub>2</sub> O <sub>3</sub>	6.00E-06	YbFCO <sub>3</sub>	7.68E-06
Lu <sub>2</sub> O <sub>3</sub>	1.00E-06	LuFCO <sub>3</sub>	1.28E-06
Y <sub>2</sub> O <sub>3</sub>	9.13E-04	YFCO <sub>3</sub>	1.36E-03
Total	9.99E-01	Total	1.30E+00

Table 2: Monazite REO and mineral composition

Rare Earth Oxide	Fraction of Monazite Rare Earth Oxide Content (kg/kg TREO) (Gupta and Krishnamurthy, 2005)	Monazite Component	Fraction of monazite (kg bastnaesite/kg TREO)
CeO <sub>2</sub>	4.27E-01	CePO <sub>4</sub>	5.83E-01
La <sub>2</sub> O <sub>3</sub>	2.34E-01	LaPO <sub>4</sub>	3.35E-01
Pr <sub>6</sub> O <sub>11</sub>	4.10E-02	PrPO <sub>4</sub>	5.68E-02
Nd <sub>2</sub> O <sub>3</sub>	1.70E-01	NdPO <sub>4</sub>	2.42E-01
Sm <sub>2</sub> O <sub>3</sub>	3.00E-02	SmPO <sub>4</sub>	4.22E-02
Eu <sub>2</sub> O <sub>3</sub>	1.00E-03	EuPO <sub>4</sub>	1.40E-03
Gd <sub>2</sub> O <sub>3</sub>	2.03E-02	GdPO <sub>4</sub>	2.82E-02
Tb <sub>4</sub> O <sub>7</sub>	7.00E-03	TbPO <sub>4</sub>	9.51E-03
Dy <sub>2</sub> O <sub>3</sub>	8.00E-03	DyPO <sub>4</sub>	1.10E-02
Ho <sub>2</sub> O <sub>3</sub>	1.20E-03	HoPO <sub>4</sub>	1.65E-03
Er <sub>2</sub> O <sub>3</sub>	3.00E-03	ErPO <sub>4</sub>	4.11E-03
Tm <sub>2</sub> O <sub>3</sub>	0.00E+00	TmPO <sub>4</sub>	0.00E+00
Yb <sub>2</sub> O <sub>3</sub>	2.40E-02	YbPO <sub>4</sub>	3.26E-02
Lu <sub>2</sub> O <sub>3</sub>	1.40E-03	LuPO <sub>4</sub>	1.90E-03
Y <sub>2</sub> O <sub>3</sub>	2.40E-02	YPO <sub>4</sub>	3.91E-02
Total	9.91E-01	Total	1.39E+00

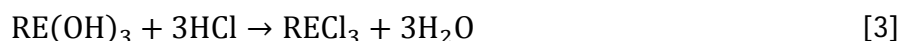
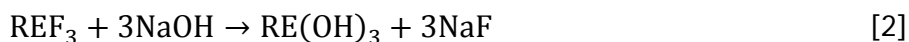
The chemical reactions for leaching are broken up by solvent type below. The bulk of the calculations in the DS determine material inputs and emissions according to these reactions. The bastnaesite with hydrochloric acid reactions are shown in **Equations [1]** through **[3]** (Gupta & Krishnamurthy, 2005). The sulfuric acid reactions with both bastnaesite and monazite/xenotime are shown in **Equations [4]** through **[8]**. Note that the initial products are the only differences between processing either mineral with sulfuric acid (i.e., **Equations [6]** through **[8]** are shared for both minerals) (Gupta & Krishnamurthy; Habashi, 2013). The monazite/xenotime with caustic soda reactions are

shown in **Equations [9]** through **[10]**. The final product for all three groups is a mix of rare earth chloride hydrates ( $\text{RECl}_3 \cdot 6\text{H}_2\text{O}$ ) to be sent for further processing (Gupta & Krishnamurthy)

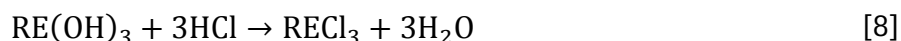
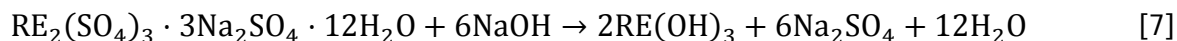
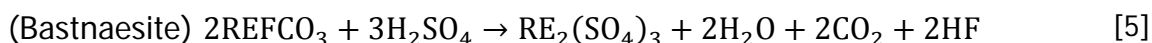
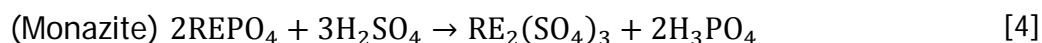
### Bastnaesite – Hydrochloric acid



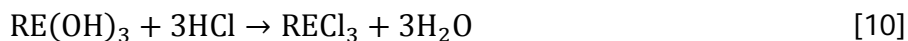
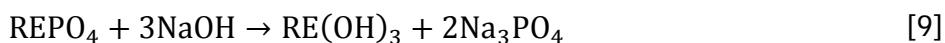
Where RE represents all rare earth elements other than cerium (La, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y, and Sc)



### Bastnaesite or Monazite/Xenotime – Sulfuric acid



### Monazite/Xenotime – Caustic soda



The temperatures of the leaching processes vary according to the material and solvent combination. For bastnaesite and hydrochloric acid the temperature is 93°C, held for 4 hours (Gupta & Krishnamurthy, 2005). For monazite and sulfuric acid, the temperature is 200°C for 2-4 hours (the model uses 4 hours by default), while the temperature for bastnaesite and sulfuric acid is 500°C with time assumed to be 4 hours (Habashi, 2013; Gupta & Krishnamurthy). And for monazite/xenotime and caustic soda, the temperature is 160°C held for 3 hours (Habashi).

Rather than assume a specific type of heat generation including efficiencies, this unit process estimates the heat required to heat the mixture from 20°C to the required temperature, **Equation [11]**. The specific heat of water is at 20°C is used for the mixture to simplify the process. Heat loss is estimated assuming that the leach reactor is lined with 0.1524-m (6-inch) firebrick for insulation with a total of surface area of 6 m<sup>2</sup> (a cube with edge length of 1 meter), **Equation [12]** (DOE, 2009). Insulation values are provided for 0.0762-m (3-inch) and 0.3048-m (12-inch) thick firebrick to provide a range of uncertainty.

$$Q_h = c_p \frac{J}{g \cdot \Delta K} \cdot (T_f - T_i) K \cdot 1 \text{ kg} \cdot \frac{1000 \text{ g}}{\text{kg}} \cdot \frac{1 \text{ kJ}}{1000 \text{ J}} \quad [11]$$

where,

$Q_h$  is the heat required to heat the bastnaesite to calcination temperature (kJ)

$c_p$  is the specific heat of water (4.1840 J/g-K)

$T_f$  is the final temperature (varies)

$T_i$  is the initial temperature (20°C)

$$Q_l = U_{ins} \frac{J}{\text{hr} \cdot \text{m}^2 \cdot \Delta K} \cdot A \text{ m}^2 \cdot t \text{ hr} \cdot (T_{\text{reactor}} - T_{\text{amb}}) K \cdot \frac{\text{kJ}}{1000 \text{ J}} \quad [12]$$

where,

$Q_l$  is the heat loss during calcination (kJ)

$U_{ins}$  is the heat transfer coefficient (5.7686 J/hr-m<sup>2</sup>-ΔK)

$T_{\text{reactor}}$  is the temperature inside the reactor (varies)

$T_{\text{amb}}$  is the ambient temperature (20°C)

$A$  is the surface area of the reactor (6 m<sup>2</sup>)

$t$  is the time for calcination (4 hrs)

In addition to adjusting the binary parameters to select the scenarios, the values for the other required parameters are shown in **Table 3**. The TREO for bastnaesite rare earth concentrate was set based on the typical output of flotation beneficiation for Mountain Pass – 0.72 kg TREO/kg of rare earth concentrate (Pradip & Fuerstenau, 2013). The TREO for monazite was set so that the mass of mineral content is equal to the mass of bastnaesite content – 0.67 kg TREO/kg of rare earth concentrate. The molecular weight of the mix of elemental rare earths was determined from the mineral contents defined in **Tables 1** and **2** and as previously described.

**Table 3: Parameters used for scenario results in Table 4**

Parameter Description	Parameter Name	Bastnaesite	Monazite	Unit
Total rare earth oxide content of rare earth concentrate	ore_frac_reo	0.72	0.6743	kg TREO/kg rare earth concentrate
Mass of mineral per mass of TREO	RE_ore_conv	1.301	1.389	kg mineral/kg TREO
Molecular weight of mix of rare earth elements	mol_wt_re	0.1403	0.1404	kg RE/mol RE mix

Results for each of the scenarios are provided in **Table 4**.

**Table 4: Unit Process Input and Output Flows**

Flow Name	Bastnaesite w/ HCl Acid	Bastnaesite w/ H <sub>2</sub> SO <sub>4</sub> Acid	Monazite w/ H <sub>2</sub> SO <sub>4</sub> Acid	Monazite w/ Caustic Soda	Units (Per Reference Flow)
<b>Inputs</b>					
rare earth ore concentrate	1.00E+00	1.00E+00	1.00E+00	1.00E+00	kg
Hydrochloric acid (100%)	6.23E-01	4.67E-01	4.35E-01	4.35E-01	kg
Sulphuric acid aq. (100%)	0.00E+00	1.26E+00	1.17E+00	0.00E+00	kg
Sodium hydroxide (100%; caustic soda)	5.69E-02	5.12E-01	4.78E-01	4.78E-01	kg
Water	1.09E+00	5.09E-01	4.74E-01	6.93E-01	kg
Sodium chloride	0.00E+00	7.49E-01	6.98E-01	0.00E+00	kg
Heat, from Mountain Pass CHP	7.91E+02	3.43E+03	1.25E+03	1.16E+03	kJ
<b>Outputs</b>					
rare earth chloride concentrate	1.51E+00	1.51E+00	1.41E+00	1.41E+00	kg
Carbon dioxide [Inorganic emissions to air]	1.88E-01	1.88E-01	0.00E+00	0.00E+00	kg
Hydrogen fluoride [Inorganic emissions to air]	0.00E+00	8.54E-02	0.00E+00	0.00E+00	kg
Phosphoric acid waste	0.00E+00	0.00E+00	4.34E-01	0.00E+00	kg
solid waste	6.35E-02	6.35E-02	6.35E-02	6.35E-02	kg
dilute acid waste	9.38E-01	2.52E+00	2.35E+00	0.00E+00	kg
Trisodium phosphate waste	0.00E+00	0.00E+00	0.00E+00	1.13E+00	kg
sodium fluoride	1.79E-01	0.00E+00	0.00E+00	0.00E+00	kg

\* **Bold face** clarifies that the value shown *does not* include upstream environmental flows.

## Embedded Unit Processes

None.

## References

- DOE (2009). Maximize System Efficiency with Proper Insulation. Energy Matters, Winter 2009. Retrieved 3/3/2014 from [http://www1.eere.energy.gov/manufacturing/tech\\_assistance/winter2009.html](http://www1.eere.energy.gov/manufacturing/tech_assistance/winter2009.html)
- Gupta, C.K. and Krishnamurthy, N. (2005). Extractive Metallurgy of Rare Earths. Boca Raton, FL: CRC Press.
- Habashi, F. (2013). Extractive metallurgy of rare earths. Canadian Metallurgical Quarterly, 52(3), 224-233. doi: doi:10.1179/1879139513Y.0000000081
- Pradip, C. & Fuerstenau, W. (2013a). The Synthesis and Characterization of Rare-Earth Fluocarbonates. *KONA Powder and Particle Journal No. 30*. Hosokawa Powder Technology Foundation.



Pradip, Fuerstenau D.W. (2013b). Design and development of novel flotation reagents for the beneficiation of Mountain Pass rare-earth ore. *Minerals and Metallurgical Processing*. Vol. 30, No. 1, pp. 1-9.



**Section III: Document Control Information**

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Original/no revisions

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