NETL Life Cycle Inventory Data
Process Documentation File

Process Name: Rare earths solvent extraction

Reference Flow: 1 kg of rare earth chloride concentrate input

Brief Description: Separation of rare earth chlorides using di-(2-ethylhexyl)-phosphoric acid and mixer-settlers

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: Yes

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:

motor_factor	*[Wh/l] Motor electricity for each mixer settler stage*
man_ext_stages	*[stages] Number of extraction stages - manual*
scrub_stages	*[stages] Number of scrubbing stages*
strip_stages	*[stages] Number of stripping stages*

recovery_rate	*[kg/kg] kg of rare earth chloride recovered per kg rare earth chloride input*
auto_ext_stage	*[binary] Automatically calculate number of extraction stages*
Ce_out	*[binary] Selects Ce chloride hexahydrate as output for the process*
La_out	*[binary] Selects La chloride hexahydrate as output for the process*
Pr_out	*[binary] Selects Pr chloride hexahydrate as output for the process*
Nd_out	*[binary] Selects Nd chloride hexahydrate as output for the process*
Sm_out	*[binary] Selects Sm chloride hexahydrate as output for the process*
Eu_out	*[binary] Selects Eu chloride hexahydrate as output for the process*
Gd_out	*[binary] Selects Gd chloride hexahydrate as output for the process*
Tb_out	*[binary] Selects Tb chloride hexahydrate as output for the process*
Dy_out	*[binary] Selects Dy chloride hexahydrate as output for the process*
Ho_out	*[binary] Selects Ho chloride hexahydrate as output for the process*
Er_out	*[binary] Selects Er chloride hexahydrate as output for the process*
Tm_out	*[binary] Selects Tm chloride hexahydrate as output for the process*
Yb_out	*[binary] Selects Yb chloride hexahydrate as output for the process*
Lu_out	*[binary] Selects Lu chloride hexahydrate as output for the process*
Y_out	*[binary] Selects Y chloride hexahydrate as output for the process*

Ce_conc	*[kg/kg] mass of Ce chloride hexahydrate per kg of rare earth chloride concentrate input*
La_conc	*[kg/kg] mass of La chloride hexahydrate per kg of rare earth chloride concentrate input*
Pr_conc	*[kg/kg] mass of Pr chloride hexahydrate per kg of rare earth chloride concentrate input*
Nd_conc	*[kg/kg] mass of Nd chloride hexahydrate per kg of rare earth chloride concentrate input*
Sm_conc	*[kg/kg] mass of Sm chloride hexahydrate per kg of rare earth chloride concentrate input*
Eu_conc	*[kg/kg] mass of Eu chloride hexahydrate per kg of rare earth chloride concentrate input*
Gd_conc	*[kg/kg] mass of Gd chloride hexahydrate per kg of rare earth chloride concentrate input*
Tb_conc	*[kg/kg] mass of Tb chloride hexahydrate per kg of rare earth chloride concentrate input*
Dy_conc	*[kg/kg] mass of Dy chloride hexahydrate per kg of rare earth chloride concentrate input*
Ho_conc	*[kg/kg] mass of Ho chloride hexahydrate per kg of rare earth chloride concentrate input*
Er_conc	*[kg/kg] mass of Er chloride hexahydrate per kg of rare earth chloride concentrate input*
Tm_conc	*[kg/kg] mass of Tm chloride hexahydrate per kg of rare earth chloride concentrate input*
Yb_conc	*[kg/kg] mass of Yb chloride hexahydrate per kg of rare earth chloride concentrate input*

Lu_conc	*[kg/kg] mass of Lu chloride hexahydrate per kg of rare earth chloride concentrate input*
Y_conc	*[kg/kg] mass of Y chloride hexahydrate per kg of rare earth chloride concentrate input*

Tracked Input Flows:

rare earth chloride concentrate	*[Technosphere] Reference flow - rare earth chloride hydrate concentrate*
di-(2-ethylhexyl)phosphoric acid solvent	*[Technosphere] Makeup solvent*
Water (Unspecified) [Water]	*[Resource] Water to mix with dry rare earth chloride hydrate concentrate*
Kerosene	*[Resource] Kerosene to mix with solvent*
Caustic soda (50%)	*[Resource] Caustic soda*
Electricity	*[Technosphere] Electricity*

Tracked Output Flows:

Rare earth chloride hexahydrate	*[Intermediate product] Rare earth chloride hexahydrate*
Water, to treatment	*[Waste flow] Water to treatment*

Section II: Process Description

Associated Documentation

This unit process is composed of this document and the data sheet (DS) *DS_Stage1_O_rare_earth_solvent_extraction_2014.01.xlsx*, which provides additional details regarding relevant calculations, data quality, and references.

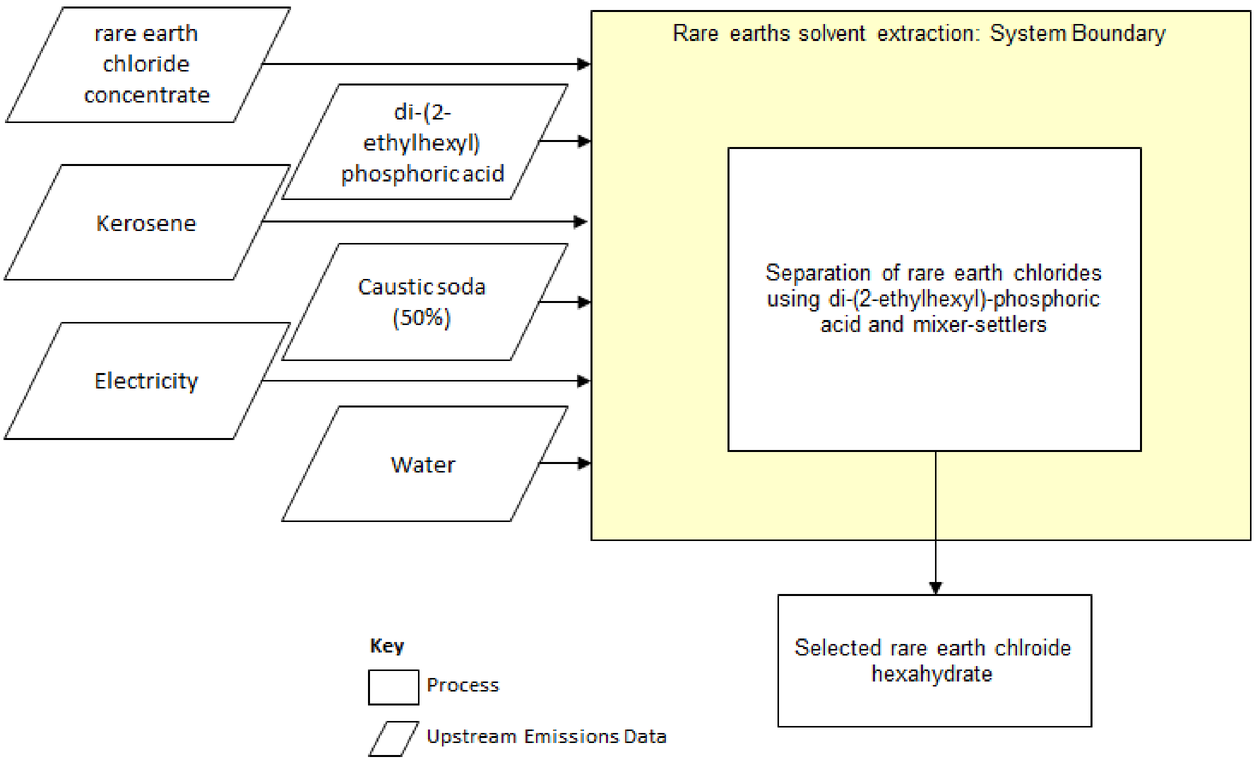
Goal and Scope

This unit process provides a summary of relevant input and output flows associated with separating a single rare earth chloride from a mix of rare earth chloride hydrates. The material and energy requirements are calculated to target a specific rare earth chloride rather than the requirements for processing the whole stream with 15 co-products, thus acting as a form of allocation. The reference flow of this unit process is: 1 kg of rare earth chloride concentrate input.

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 the di-(2-ethylhexyl)-phosphoric acid (DEHPA), kerosene, caustic soda (50%), electricity, rare earth concentrate, and water are calculated other unit processes. The methods for calculating these operating activities are described below.

Figure 1: Unit Process Scope and Boundary



This unit process models a solvent extraction system that is made up of counter-current mixer-settlers with a feed solution of aqueous mixed rare earth chlorides and an organic-phase solvent made up of a mix of DEHPA and kerosene (Gupta and Krishnamurthy, 2005). The range of rare earth ions that are transferred to the organic-phase solvent is dependent on the pH of the aqueous solution specifically a higher H+ activity results in a higher separation point within the lanthanide series (Kronholm et al., 2013). Ordinarily, a mixed rare earth chloride stream would be sent through multiple extraction circuits to separate all desired rare earth elements from the stream. For example, the first circuit would separate the light rare earth elements (LREEs) and the heavy rare earth elements (HREEs). These separated rare earth groups would undergo another separation to target specific elements, so one element might need to go through 4 or more circuits before it is separated from the rest. This unit process allows the selection of any individual rare earth and assumes that the only processing that needs to be done is to separate a single rare earth from all others above or below it in the lanthanide series. For the majority of elements, this results in two separate extraction circuits, but only one for lanthanum (the first in the series) and lutetium (the last in the series).

Within each extraction circuit, there are multiple stages of mixer-settlers to achieve the desired purity of a particular stream, and each extraction circuit is comprised of a set of extraction, scrubbing, and stripping mixer-settlers. The number of required extraction stages can be manually specified by the user, if data is known, or there is also the option to have that number calculated based on separation factors between each element. There are a few assumptions made to generate the function used to calculate the stages. First, a minimum number of 2 stages are required to separate rare earths with a separation factor of 200 or above. Second, materials with a separation factor of 1 cannot be separated, thus requiring an infinite number of stages. A modified power equation will provide these required asymptotes, see **Equation [1]**. The modifications are necessary to provide a positive, non-zero asymptote (c) and a vertical asymptote at 1 (x-1). From there, it is assumed that separation factors of 5, 3, and 2 will require 5, 6, and 7 stages respectively. Fitting these points with the other assumptions provides **Equation [2]**.

$$number_{stages} = a \cdot (x-1)^{b} + c \quad \textbf{[1]}$$

where
a,b, and c are calculated coefficients
x is the separation factor

$$number_{stages} = 6.42 \cdot (x-1)^{-0.31} + 0.77 \quad \textbf{[2]}$$

After extraction, the organic phase containing rare earths is scrubbed to remove the unwanted rare earths and other impurities contained in the organic phase (Kronholm et el., 2013). This is accomplished by recycling an aqueous phase solution high in the target rare earth (Kronholm et el., 2013). For this unit process the default number of scrubbing stages is set to 7 for each stage based the average number of scrubbing stages in solvent extraction systems in *Extractive Metallurgy of Rare Earths* (Gupta & Krishnamurthy, 2005).

Once the organic phase contains the target rare earth(s) in sufficient purity, the loaded organic is stripped to return the rare earths to the aqueous phase. Again the default number of stages (5 for each stage) for this is based on the average number of stripping stages in solvent extraction systems in *Extractive Metallurgy of Rare Earths* (Gupta & Krishnamurthy, 2005).

The default recovery rate (0.96 kg of rare earth chloride product per kg of rare earth chloride input) is applied to all of the different rare earths and is based on the recovery rate of the Mountain Pass solvent extraction process (Molycorp, 2010). The recovery rate is also used to mass allocate the mixed rare earth chloride feedstock according to product yield by dividing the yield by the recovery rate. This means that the rest of the rare earth chloride mix is treated as a co-product, and they are burdened with the upstream emissions according to the mass of the remaining mix.

Material inputs of DEHPA, caustic soda, and kerosene are calculated by combining yearly material consumption from Mountain Pass with the calculated number of mixer-settler stages for the entire range of rare earths by this unit process - 644 stages (ENSR International, 2004). The results are kg of material required per stage of processing, which are then multiplied by the calculated number of stages for the selected rare earth.

Table 1 shows the energy and material requirements for the different rare earths.

Table 1: Unit Process Input and Output Flows

Flow Name	$CeCl_3$	$LaCl_3$	$PrCl_3$	$NdCl_3$	$SmCl_3$	$EuCl_3$	$GdCl_3$	$TbCl_3$	Units (Per Reference Flow)
Inputs									
rare earth chloride concentrate	4.81E-01	3.42E-01	4.31E-02	1.22E-01	7.85E-03	1.17E-03	1.62E-03	1.51E-04	
di-(2-ethylhexyl)phosphoric acid solvent	5.62E-05	2.93E-05	6.85E-05	5.50E-05	4.40E-05	4.77E-05	4.89E-05	5.01E-05	kg
Water (Unspecified) [Water]	7.87E-01	5.60E-01	7.05E-02	1.99E-01	1.28E-02	1.91E-03	2.65E-03	2.47E-04	kg
Kerosene	4.56E-04	2.38E-04	5.55E-04	4.46E-04	3.57E-04	3.87E-04	3.97E-04	4.07E-04	kg
Caustic soda (50%)	1.89E-02	9.86E-03	2.30E-02	1.85E-02	1.48E-02	1.60E-02	1.64E-02	1.68E-02	kg
Electricity	1.22E+00	4.54E-01	1.33E-01	3.02E-01	1.56E-02	2.52E-03	3.57E-03	3.42E-04	Wh
Outputs									
Rare earth chloride hexahydrate	4.62E-01	3.29E-01	4.13E-02	1.17E-01	7.53E-03	1.12E-03	1.55E-03	1.45E-04	kg
Water, to treatment	7.87E-01	5.60E-01	7.05E-02	1.99E-01	1.28E-02	1.91E-03	2.65E-03	2.47E-04	kg

Flow Name	$DyCl_3$	$HoCl_3$	$ErCl_3$	$TmCl_3$	$YbCl_3$	$LuCl_3$	YCl_3	Units (Per Reference Flow)
Inputs								
rare earth chloride concentrate	3.00E-04	4.87E-05	3.32E-05	8.50E-06	5.61E-06	9.30E-07	1.17E-03	
di-(2-ethylhexyl)phosphoric acid solvent	5.38E-05	5.14E-05	5.14E-05	5.26E-05	6.60E-05	6.24E-05	4.89E-05	kg
Water (Unspecified) [Water]	4.91E-04	7.97E-05	5.43E-05	1.39E-05	9.18E-06	1.52E-06	1.91E-03	kg
Kerosene	4.36E-04	4.17E-04	4.17E-04	4.26E-04	5.36E-04	5.06E-04	3.97E-04	kg
Caustic soda (50%)	1.81E-02	1.73E-02	1.73E-02	1.77E-02	2.22E-02	2.10E-02	1.64E-02	kg
Electricity	7.28E-04	1.13E-04	7.70E-05	2.02E-05	1.67E-05	2.62E-06	2.58E-03	Wh
Outputs								
Rare earth chloride hexahydrate	2.88E-04	4.67E-05	3.19E-05	8.16E-06	5.38E-06	8.93E-07	1.12E-03	kg
Water, to treatment	4.90E-04	7.95E-05	5.42E-05	1.37E-05	8.88E-06	1.25E-06	1.91E-03	kg

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

Embedded Unit Processes

None.

References

ENSR International (2004). Final Environmental Impact Report for Molycorp, Inc. Mountain Pass Mine 30-Year Plan. Camarillo, CA: ENSR International.

Gupta, C.K. and Krishnamurthy, N. (2005). Extractive Metallurgy of Rare Earths. Boca Raton, FL: CRC Press Inc.

Kronholm, B., Anderson, C. G., and Taylor, P.R. (2013). A Primer on Hydrometallurgical Rare Earth Separations. *JOM, 65(10).*

Molycorp Minerals, LLC (2010). Engineering Study for Re-Start of the Mountain Pass Mine and Processing Facility. Mountain Pass, CA: Molycorp Minerals, LLC. Retrieved June 10, 2014 from http://www.sec.gov/Archives/edgar/data/1489137/000095012310065239/d74323fwfwp.htm

Section III: Document Control Information

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