Monazite Ore Processing for Rare Earth Oxides and Thorium Extraction — Part II

PEP Review 2026-02

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Glossary

$/h	Dollars per hour
$/Mgal	Dollars per thousand gallons
$/Mlb	Dollars per thousand pounds
$/t	Dollars per metric ton
AACE	Association for the Advancement of Cost Engineering
Aq	Aqueous
BFW	Boiler feedwater
bhp	Brake horsepower
BLI	Battery limits investment
°C	Degree Celsius
capex	Capital expenditure
cfm	Cubic feet per minute
¢/kWh	Cents per kilowatt-hour
¢/lb	Cents per pound
CLD	Central Lanthanide Deposit
cm	Centimeters
¢/Mgal	Cents per thousand gallons
Conc.	Concentrated
DBBP	Dibutyl phenyl phosphate
DEHPA	Di(2-ethylhexyl) phosphoric acid
EHEHPA	2-Ethylhexyl phosphonic acid mono-2-ethylhexyl ester
EPC	Engineering, procurement and construction
ETP	Effluent treatment plant
EV	Electric vehicle
°F	Degree Fahrenheit
FCC	Fluid catalytic cracking
FOB	Free/freight on board
ft	Feet
FRP	fiberglass reinforced plastic
G&A	General and administrative
g/L	Grams per liter
gal	Gallons
gal/lb	Gallons per pound
gpm	Gallons per minute
HDPE	High-density polyethylene
HEHEHP	2-ethylhexyl hydrogen -2-ethylhexylphosphonate
HEV	Hybrid electric vehicle
hp	Horsepower
H-$RECl_3$	Heavy rare-earth chloride
HREE	Heavy rare-earth element
HVAC	Heating, ventilation, and air conditioning
IUPAC	International Union of Pure and Applied Chemistry
kg	Kilograms
kg/h	Kilograms per hour
kPa	Kilopascals
kW	Kilowatt
kWh	Kilowatt-hour
kWh/kg	Kilowatt-hour per kilogram
lb	Pounds
lb/h	Pounds per hour
lb/lb	Pounds per pound
LIX54	1-Phenyl-3-isoheptyl-1,3-propanedione
LPS	Low-pressure steam
LREE	Light rare-earth element
µ	Micron

m	Meters
M	molar
Mlb/h	Thousand pounds per hour
MMBtu/h	Million British thermal units per hour
MMlb/y	Million pounds per year
M-$RECl_3$	Medium rare-earth chloride
MREE	Medium rare-earth element
Mt/Mt	Thousand metric tons per thousand metric tons
N	Normality
opex	Operating expenditure
Org	Organic
OSBL	Outside battery limits
P229	Bis(2-ethylhexyl) phosphoric acid
P507	2,4,4-Trimethylpentyl phosphonic acid
PC88A	2-Ethylhexyl 2-ethylhexyphosphonic acid
PEP	Process Economics Program
PFD	Process flow diagram
Ppt	Precipitate
psia	Pounds per square inch absolute
psig	Pounds per square inch gauge
PTFE	Polytetrafluoroethylene
R&D	research and development
RE	Rare earth
$RECl_3$	Rare-earth chloride
REE	Rare-earth element
REM	Rare-earth mineral
REO	Rare-earth oxide
$RE(OH)_3$	Rare-earth hydroxide
ROI	Return on investment
ROM	Run-of-mine
sq ft	Square feet
SS	Stainless steel
TBP	Tributyl phosphate
t/d	Metric tons per day
t/h	Metric tons per hour
t/t	Metric tons per metric ton
t/y	Metric tons per year
TIG	Tungsten inert gas
USGC	United States Gulf Coast
TFC	Total fixed capital
TREO	Total rare earth oxide
TOPO	Trioctylphosphine oxide
wt%	Weight percent
y	Years

Abstract

Advancements in green technologies, expansion of electronics and automotive industries, and thorium (Th)-based nuclear reactors are the primary driving factors promoting the significance of rare-earth minerals (REMs) and thorium. The market for light rare-earth elements (LREEs), particularly neodymium (Nd) and praseodymium (Pr), is expected to expand significantly as attention turns to renewable energy sources. NdPr oxide is the primary raw material for permanent magnets (neodymium-iron-boron [NdFeB] magnets) in wind turbines and electric vehicles (EVs). Nearly 70%-80% of the total value of the rare-earth oxide (REO) sector is derived from the market for permanent magnets. Recently, thorium-based nuclear reactors have gained interest than conventional uranium nuclear reactors because of key advantages, such as an abundance of thorium, higher fuel efficiency, reduction in nuclear waste, passive safety mechanisms, and low-cost in enrichment process.

Monazite is a phosphate mineral, comprising mainly of rare-earth elements (REEs) and thorium. Monazite occurs as an accessory mineral in acidic igneous rocks, metamorphic rocks, and certain vein deposits. The Asia-Pacific region dominates the global monazite market because of its significant monazite reserves and strong industrial growth, as well as its extensive mining and processing capabilities. Mainland China's dominance in the REE market drives the demand for monazite. However, rearranging the manufacturing chain globally would be crucial as it would help in reducing the reliance on mainland China for the extraction of REEs and thorium from the monazite ore.

The production of REEs (in the form of chlorides) from monazite ore, belonging to the Central Lanthanide Deposit (CLD), Mount Weld, Australia, has been covered in part I (RW2025-10) of this review series. This review (part II) covers the production of REOs (especially NdPr oxide as the main product and lanthanum oxide and thorium oxide as coproducts) utilizing rare-earth chloride ($RECl_3$) as an intermediate compound (production of $RECl_3$ is discussed in part I of this review series, RW2025-10). To produce REO from $RECl_3$ of monazite CLD, Mount Weld, Australia, 200 grams per liter (g/L) of $RECl_3$ feed is subjected to solvent extraction with 50% saponified PC88A in 1.5 molar (M) kerosene, followed by the scrubbing and stripping (two-phase) steps, resulting in light-$RECl_3$ (La, Nd, and Pr), medium-$RECl_3$ (Sm and Eu), and heavy-$RECl_3$(Tb and Gd) concentrates. The light-$RECl_3$ concentrate is further subjected to the solvent extraction step, using 50% saponified PC88A in 1.5M kerosene, to produce individual rare-earth chlorides and are further precipitated as RE-oxalates using oxalic acid followed by calcination to produce individual REOs (Nd_2O_3 and Pr_2O_3). The individual Nd_2O_3 and Pr_2O_3 are further mixed in 1:2 molar ratio and are calcined to obtain NdPr oxide. The medium rare-earth chloride (M-$RECl_3$) and heavy rare-earth chloride (H-$RECl_3$) concentrates are further concentrated via evaporation followed by crystallization to produce mixed $RECl_3$. The plant also produces thorium oxide from the thorium hydroxide raw cake obtained in the review series part I. The thorium hydroxide raw cake is subjected to acid-digestion with hydrochloric acid (HCl) to obtain thorium chloride, followed by precipitation with oxalic acid to obtain thorium oxalates. The thorium oxalates are further calcined to produce thorium oxide. Part II of this analysis includes an economic evaluation for a mineral processing plant, located at a US Gulf Coast (USGC), that can produce 7.71 million pounds per year (MMlb/y) (3,497.2 metric tons per year [t/y]) of NdPr oxide from $RECl_3$ as an intermediate compound (obtained from monazite ore from CLD Mount Weld, Australia). The technology presented here would be of great interest to industrial sectors and grassroots plants willing to use monazite ore metallurgical and extractive processing for REMs and thorium.

The Process Economics Program (PEP) has not covered ore processing technologies, especially REM extraction from monazite ore, until now. Hence, this review series has evaluated the monazite ore processing of geological origin from CLD at Mount Weld, Australia, to produce REO (especially NdPr oxide) and thorium oxide. Part I has described the capital expenditure (capex) and operating expenditure (opex) to produce mixed-$RECl_3$ from the ore. Part II of the review evaluates the economics of REO, especially 99.9% NdPr oxide, and others such as Nd_2O_3 and mixed $RECl_3$ containing La, Sm, Eu, Tb, and Dy, as well as thorium oxide production. The technology discussed here would be of major interest to industrial sectors or grassroots plants willing to employ monazite ore metallurgical and extractive processing, as well as the manufacturers of REO and thorium oxide. We have estimated the capex and opex for the process to produce 7.71 MMlb/y of NdPr oxide from $RECl_3$ at a USGC location, using a PEP Cost Index of 1,608 (fourth quarter of 2024). This is in continuation of the technology (production of 60.72 metric tons per day [t/d] of $RECl_3$) discussed in part I of this review series.

The process flow diagrams, material balance, major equipment list with specifications, cost information for battery limits, variable costs, capex and opex, and total production costs are evaluated in this analysis. The technological and economic assessment of the process is the PEP's independent interpretation of a potential commercial process. Each of these is based on the information presented in the open literature, such as patents and technical articles, and may not reflect in whole or in part the actual plant configuration. We do believe that these sources are sufficient to represent the process and

process economics within the range of accuracy necessary for the economic evaluations of the conceptual process designs.

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