Processing and Refining of Tin Tailing Mining

N D Pusporini, Suyanti, R A Amiliana and H Poernomo
Center for Accelerator Science and Technology, National Nuclear Energy Agency
E-mail: nur.dewi@batan.go.id

Abstract. Exploration and production of tin massively has an impact in the quantity of tailing production. The tailing contains various strategic metal-carrying minerals, namely monazite, xenotime, zircon and ilmenite. By the right process, these minerals can be purified into high-value metals such as rare earth elements, Zr and Ti. The research purpose is conducting a study towards processing and refining technology of tin tailing. The study was performed by analyzing the composition of Bangka tin tailing using XRF. Based on these information, flow diagram of processing and refining technology of monazite to Ce$_2$O$_3$, La$_2$O$_3$ and concentrated Nd(OH)$_3$; xenotime to concentrated Y$_2$O$_3$; zircon to ZrO$_2$ and ilmenite to TiO$_2$ have been generated. The result showed that processing and refining of tin tailing mining contained mineral monazite, xenotime, zircon and ilmenite could be carried out. However, it is still necessary to further develop the process by giving highly attention to the economic concept.

1. Introduction
Indonesia as one of the largest tin producer country in the world has production capacity of 62,877 tons/year in 2016 [1]. Tin metal is quite extensive to be applied, such as for corrosion-resistant coatings, superconducting magnets and as a metal alloy, so that high exploration and production activities are needed. However, it must be taken that massive tin exploration and production activities have a wide environmental impact [2]. The impact can be caused by the tailing production as one.

Percent recovery of the processing and refining of minerals to separate impurities generally reached a maximum of 80%, thus 20% will become tailing. Tailing is by-product of the mining or processing of mineral ores which are regarded as hazardous waste and pollutants toward the environment. In the other hand, tailing still contains a variety of strategic minerals which with the right processes can be refined into high economic value metals.

PT Timah Tbk. as one of the permitted holders of tin mining business in Bangka has established a cooperation with the National Nuclear Energy Agency of Indonesia (BATAN) on purifying tin tailing to get Rare Earth Elements (REE), Zr and Ti. The applications of these metals are very wide covering health, energy, food, environment, transportation, information and communication, defense and security sectors and material technology [3]. Therefore, it is not surprising that research and development related to these strategic minerals remain as a priority research in Indonesia until 2045 [4].

Rare earth elements, Zr and Ti or called as rare metals are referred not only as commodities but also as national strategic reserves. The total potential deposits of these metals in Indonesia reach 1.5 billion tons with 7 million tons of tailing or by-products of tin mining in Bangka Belitung Province. The tailing contains various strategic metal-carrying minerals, namely ilmenite (32.43%), zircon (16.65%), cassiterite (12.59%), monazite (11.76%) and xenotime (10.82% of monazite) [5].

Many research has been done on the processing and refining of strategic metals from tin tailing mining. In addition, tin tailing also contains radioactive elements, so a special treatment in processing is needed to lower radiation exposure.

2. Methodology
This research was conducted using the following method:

a. Provision of mineral monazite, xenotime, zircon, and ilmenite from tin tailing mining in Bangka
area obtained from PT. Timah, Tbk.
b. Analysis of oxide compounds in the samples from each mineral has been done by using XRF (X-Ray Fluorescence).
c. Conceptualizing the processing and refining technology shown in the form of process flow diagram, are based on both metallurgical test work and laboratory process. The prospect of world needs and market share were considered.

3. Result and Discussion

3.1. Processing and Refining of Monazite. Monazite, as an associated of tin mining byproducts, is a radioactive mineral in accordance with the government regulation No. 23 of 2010. Therefore, monazite is a natural radioactive substance that because of human activities has increased its radioactivity or called as TENORM. Monazite byproduct of the tin mining process consists of several compounds as listed in Table 1 [6]. Based on the data, it can be seen that the dominated strategic metal is rare earth group.

| Table 1. Monazite Composition from Tin Tailing Mining |
|-------------------------------|-----------------|
| Compound          | wt, %          |
| YPO₄               | 5.28           |
| LaPO₄             | 15.59          |
| CePO₄             | 37.23          |
| PrPO₄             | 3.51           |
| NdPO₄             | 12.94          |
| SmPO₄             | 2.28           |
| GdPO₄             | 2.27           |
| DyPO₄             | 1.17           |
| ErPO₄             | 0.46           |
| YbPO₄             | 0.35           |
| Th₃(PO₄)₄         | 13.96          |
| (UO₂)₃(PO₄)₂      | 0.59           |

Separation of REE from monazite required long process stage because it also contains uranium (U), thorium (Th) and phosphate. The Center for Nuclear Material Technology (CNMT) - BATAN already has a pilot plant to separate REE from radioactive elements of U and Th. The technology adopted in this pilot plant was monazite processing decomposition at 150 °C for 2 hours using NaOH 70% [7]. The selection of this process was based on the simplicity of the process and economic considerations compared to the acid method using H₂SO₄ [6].

Processing of monazite sand by the base method was aimed to break the structure of phosphate bonds. The decomposition results were partially dissolved using HCl and then the deposition process was continued to obtain RE(OH)₃, UO₂(OH₂) and Th(OH)₄. Rare earth hydroxide (REOH) produced by monazite is further separated and purified at the pilot plant of the Center for Science and Accelerator Technology (CSAT) - BATAN.

In CSAT pilot plant, REOH was purified into REE oxide. REOH was dissolved in high concentrations of HNO₃ and heated at 135 °C. Nitric acid solution in high concentrations was a good oxidizing agent so that when it contacted with REOH, the element Ce(III) would undergo an oxidation reaction so that it turned into Ce(IV) while La(II) and Nd(II) would convert to La(III) and Nd(III). The valence difference between Ce and La and Nd would make the separation process of the three easier [8].

\[
\text{RE(OH)}_3 + 3\text{HNO}_3 \rightarrow \text{RE(NO}_3)_3 + 3\text{H}_2\text{O}
\]
\[2\text{Ce(NO}_3\text{)}_3 + 2\text{HNO}_3 + 0.5\text{O}_2 \rightarrow 2\text{Ce(NO}_3\text{)}_4 + \text{H}_2\text{O}\] (2)

RE-nitrate from the process of dissolving REOH with HNO\textsubscript{3} was then precipitated. The Ce(IV) element that compounded in RE-nitrate, precipitated by conditioning the solution at pH 4. It was done by adding NH\textsubscript{4}OH solution. The residue of Ce(OH)\textsubscript{4} was separated from the RE-nitrate filtrate by using filter. Then, precipitated RE-nitrate was conditioned at pH 8.5 by adding NH\textsubscript{4}OH to precipitate Nd(OH)\textsubscript{3}. The precipitated Nd(OH)\textsubscript{3} was separated from the RE-nitrate filtrate by filtration, then the precipitation of La(OH)\textsubscript{3} resulting from the deposition of Nd(OH)\textsubscript{3} filtration. The deposition of La(OH)\textsubscript{3} to be La\textsubscript{2}(C\textsubscript{2}O\textsubscript{4})\textsubscript{3} was carried out by adding the H\textsubscript{2}C\textsubscript{2}O\textsubscript{4} solution. The Ce(OH)\textsubscript{4} and La\textsubscript{2}(C\textsubscript{2}O\textsubscript{4})\textsubscript{3} residues were then calcined to get CeO\textsubscript{2} and La\textsubscript{2}O\textsubscript{3} products.

\[
\text{Ce(NO}_3\text{)}_4 + 4\text{NH}_4\text{OH} \rightarrow \text{Ce(OH)}_4 + 4\text{NH}_4\text{NO}_3
\] (3)

\[
\text{RE(NO}_3\text{)}_3 + 3\text{NH}_4\text{OH} \rightarrow \text{Nd(OH)}_3 + 3\text{NH}_4\text{NO}_3 + \text{La(NO}_3\text{)}_3
\] (4)

\[
2\text{La(NO}_3\text{)}_3 + 3\text{H}_2\text{C}_2\text{O}_4 \rightarrow \text{La}_2(\text{C}_2\text{O}_4)_3 + 6\text{HNO}_3
\] (5)

Research and development of monazite processing from tin tailing mining in pilot plant has produced CeO\textsubscript{2} with 93% purity, La\textsubscript{2}O\textsubscript{3} with 91% purity, and concentrated Nd-hydroxide with 60% purity. The purification method for concentrated is still being developed so the purity could be more than 90%.

The concentrated Nd-hydroxide produced from the separation and purification of monazite sand still contains some significant amounts of REE such as yttrium (Y). Purification of concentrated Nd can be done by using liquid extraction [9]–[14]. The simplicity and economic consideration are becoming the selection parameters [11].

![Figure 1. Process Flow Diagram CeO\textsubscript{2}, La\textsubscript{2}O\textsubscript{3} and Nd(OH)\textsubscript{3} from Monazite](image)

The application of REE such as La, Ce, and Nd is being developed by the Non-Ministry Government Institutions in Indonesia. The CeO\textsubscript{2} as raw material for SOFC (solid oxide fuel cell), sensors and phosphor displays as is being developed by the Assessment Agency and Technology Application; La\textsubscript{2}O\textsubscript{3} as raw material for anti-radar paint is being developed by the Center for Science and Technology of Advanced Materials (CSTAM) - BATAN; and Nd\textsubscript{2}O\textsubscript{3} as a permanent magnetic material is being developed by CSTAM, Central Metal and Machinery and Universitas Indonesia (UI) [14].

The development of REE (basic monazite) refining technology is not only limited to the elements
of Ce, La, and Nd. This process will continue to be improved for other elements that also dominate, such as Pr and Sm. The element of Pr is added to zircon ceramic material as a yellow bright pigment and also functioned as optical amplification of telecommunications equipment and a scintillator for Computerized Axial Tomography or called as CAT scan. While the Sm element is applied as a mixture in making permanent magnets (Sm$_3$Co$_{17}$) and dielectric material for microwave technology [15].

3.2. Processing and Refining of Xenotime. Xenotime is a compound of REE phosphate (Y, Dy, Gd)PO$_4$ or YPO$_4$ which has tetragonal crystals, with a total percentage of REE oxide mixture ranging from 55% - 70% [16] while the radioactive of 2.2% Th and 0.05% U. Generally, xenotime is a byproduct of mining, processing, and beneficiation of heavy minerals, like cassiterite, ilmenite, zircon, and monazite in Southeast Asia. Xenotime itself is the main source of rare earth heavy elements, especially Yttrium (Y) [17]. The REE contents in xenotime minerals as a side product of the tin mining process can be shown in Table 2 [18].

| Element | wt, % |
|---------|-------|
| Y       | 60    |
| Dy      | 7.5   |
| Gd      | 3.6   |
| Lu      | 0.63  |
| Sm      | 1.2   |
| Eu      | 0.01  |
| Yb      | 6.0   |
| Tb      | 1.0   |
| Ho      | 2.0   |
| Er      | 6.2   |
| Tm      | 1.27  |

Based on the data above, the strategic metal that dominated is the REE group with the highest percentage is Yttrium (Y).

The processing and refining of rare earth metals from xenotime sand have been carried out in CSAT BATAN Yogyakarta. Since 2003, it was done to digest Y from xenotime sand by Dwi Biyantoro et al [19]. The production of rare earth oxides from that digest as the feed by using sedimentation and calcination method had also begun in 2005 [20].

The purification of xenotime sand into REE required a long process. Until now CSAT BATAN Yogyakarta has succeeded in purifying Y to 90% purity and making concentrated Y with the purity range of 65% - 80%.

The production of concentrated Y with 65% and 80% purity from xenotime sand began with digesting using sulfuric acid (H$_2$SO$_4$) and continued by quenching process. Digestion process aimed to break the molecular bonds of xenotime so that it would be easy to be dissolved and separated the impurities inside. Whereas the quenching process is a sudden cooling by using water to make REE distributed into the water phase easier.

\[ 2(\text{RE})\text{PO}_4 + 3\text{H}_2\text{SO}_4 \rightarrow \text{RE}_2(\text{SO}_4)_3 + 2\text{H}_3\text{PO}_3 \]  

The filtrate resulted from the quenching process was conditioned at pH 1.28 to facilitate the separation of thorium (Th). The pH conditioning was carried out by adding NH$_4$OH.

\[ \text{Th} (\text{SO}_4)_4 + 4\text{NH}_4\text{OH} \rightarrow \text{Th} (\text{OH})_4 + 2(\text{NH}_4)_2\text{SO}_4 \]  

The filtrate from the deposition of Th was then added with oxalic acid solution 15% to precipitate the entire metal content of the filtrate. The dried RE-oxalate was added with water and NaOH in a ratio of 1: 2: 1 at 140 °C for 2 hours. This process aimed to eliminate the carbon bonds in RE-oxalate to be more easily dissolved so that the REOH sediment could be obtained.
The dried REOH was dissolved in a high concentration of HNO₃ with weight ratio of 1 : 3 at 150 °C for 30 minutes. The filtrate then precipitated gradually by adding NH₄OH. The first precipitated was carried out by conditioning the RE(NO₃)₃ solution to acidic level (pH) of 6.5. In these conditions, concentrated Y residue was formed with REE content of Y, Dy, and Gd, respectively ± 65%, 21%, and 8.26%. The filtrate then being precipitated by the remaining Y element. This step has been done by conditioning the filtrate at pH 8. The residue obtained then being calcined to produce Y₂O₃ with purity above 80%.

![Diagram](image)

**Figure 2.** Process Flow Diagram of Y₂O₃ Concentrated from Xenotime

Yttrium, in the form of Y₂O₃, is a product of xenotime mineral processing and refining. Yttrium has wide application in the electronics, laser, ceramics, and metal alloy industries. Yttrium is also applied in fluorescent lamps and mixed materials in LCD screens to strengthen the aluminum and magnesium metal alloys [21]. Considering the usefulness, Y is incorporated into the five elements of rare earth metals that are most critically needed for industrial development, together with neodymium (Nd), dysprosium (Dy), europium (Eu), and terbium (Tb) [22].

Research on the processing and refining of REE from xenotime minerals still being continued to obtain higher purity REE from xenotime minerals. A pilot plant for xenotime sand processing is also manufactured to support the development of mineral processing research.

### 3.3. Processing and Refining of Zirconium

Zirconium (Zr) is a silvery-white metal and one of the natural element which has high range temperature and high corrosion resistance properties, both in acid and base concentrations [23]. The presence of zirconium in nature is always compounded, mainly as oxide and never as pure metal. Zirconium (Zr) to be used is in the form of zirconium silica (ZrSiO₄) which is commonly found with ilmenite and rutile (titanium minerals). In addition, the presence of zirconium sources is often associated with rare earth element minerals (REE) [24]. Zircon mineral content from tin tailing mining in Bangka can be shown in Table 3.
Zircon sand processing began with physical separation and continued with chemical purification. Physical separation was done by the beneficiation process using the high tension separator, shaking table, and magnetic separator. The purpose of the beneficiation process is to increase the zircon mineral content as chemical process feeds and to separate other minerals that mixed with zircon sand.

The refining zircon sand into zirconia \((\text{TzO}_2)\) started from smelting process of zircon sand with \(\text{NaOH}\) for 2 hours at 700°C to 800°C. The purpose of this process was to release \(\text{SiO}_2\) bonds from zircon minerals and obtain a compound that would be dissolved easier. The possible reaction are as follows.

\[
\text{ZrSiO}_4 + 2\text{NaOH} \rightarrow \text{Na}_2\text{ZrSiO}_5 + \text{H}_2\text{O} \quad (10)
\]

\[
\text{ZrSiO}_4 + 6\text{NaOH} \rightarrow \text{Na}_2\text{ZrO}_3 + \text{Na}_4\text{SiO}_4 + 3\text{H}_2\text{O} \quad (12)
\]

The next process was water leaching which aimed to dissolve the sodium silicate so it would be separated from zirconium minerals.

\[
\left(\text{Na}_2\text{ZrO}_3 + \text{Na}_2\text{SiO}_3\right) + 8\text{H}_2\text{O} \rightarrow \text{Na}_2\text{ZrO}_3 + \text{Na}_2\text{SiO}_3 + 8\text{H}_2\text{O} \quad (13)
\]

The residue from the water leaching was dried and leached with hydrochloric acid to obtain \(\text{ZrOCl}_2\) or commonly known as ZOC chemicals. The reaction is as follows.

\[
\text{Na}_2\text{ZrO}_3 + 4\text{HCl} \rightarrow \text{ZrOCl}_2 + 2\text{NaCl} + 2\text{H}_2\text{O} \quad (14)
\]

The filtrate which contained zircon was then precipitated with ammonium hydroxide at pH 10. The residue from the precipitation was washed and dried. After drying, the zircon hydroxide was calcined to form zircon oxide \((\text{TzO}_2)\) or zirconia. The reaction that occurs in the precipitation process is mentioned in equation 15 and the process flow diagram of zirconia is in Figure 3.

\[
\text{ZrOCl}_2 + 2\text{NH}_4\text{OH} + \text{H}_2\text{O} \rightarrow \text{Zr(OH)}_4 + 2\text{NH}_4\text{Cl} \quad (15)
\]

The refining zircon sand into zircon opacifier was started from the roasting process of zircon sand with \(\text{NaOH}\) for 40 minutes at temperatures 450°C. Then the roasted sand was quenched with water to dissolve the impurities element that bound with zircon compound and filtered to separate residue and filtrate. The residue was dried and ground according to the market size of zircon opacifier.

The making of zirconium sulfate \((\text{Zr(SO}_4)_2)\) was started from the sodium zirconate \((\text{Na}_2\text{ZrO}_3)\) compound that was obtained in the first process of refining zirconia. First, the sodium zirconate was dissolved with sulfuric acid. After that, it was quenched with water then crystalized. After the crystals were formed, the zircon sulfate was washed using dilute sulfuric acid then dried, so that obtained zircon sulfate with good purity.

The products of zirconium mineral processing can be differentiated in three groups, nuclear grade of zirconium, zirconium grade above 90%, and zirconium grade above 65%. Center for Science and Accelerator Technology, BATAN Yogyakarta has been succeeded in purifying zirconium with purity

| Table 3. Zircon Mineral Composition in Tin Tailing Mining |
| --- |
| Compound | wt, % |
| \(\text{ZrO}_2\) | 55.87 |
| \(\text{SiO}_2\) | 28.70 |
| \(\text{SnO}_2\) | 28.70 |
| \(\text{TiO}_2\) | 5.56 |
| \(\text{Fe}_2\text{O}_3\) | 1.90 |
| \(\text{Al}_2\text{O}_3\) | 1.57 |
| \(\text{HfO}_2\) | 0.90 |
| \(\text{ThO}_2\) | 0.16 |
| \(\text{U}_3\text{O}_8\) | 0.09 |
above 65% and 90% [25]. Zircon products with those purities can be used for various applications, for example, automotive and electronics components, oxygen sensors and solid electrolytes in fuel cells [27].

![Figure 3. Process Flow Diagram of Zirconia from Zircon Sand](image)

The nuclear grade of zirconium is used as a mixture of metal rods for nuclear reactor fuel, so it must have a high purity and the content of hafnium (Hf) elements is below 100 ppm [28]. In addition, the increased selling price of nuclear grade zirconium product is quite significant, which is around 7.8 times the price of industrial degree zirconia [24]. Therefore, further research on zirconium processing to nuclear grade is still being conducted at BATAN Yogyakarta.

3.4. Processing and Refining of Ilmenite. Ilmenite (FeTiO₃) from tin tailing mining could be obtained by the beneficiation of zircon mineral. The beneficiation of zircon mineral to increase ZrO₂ content has been done physically using a rocking table, magnetic separator, and high tension separator (HTS) to separate zircon sand from impurities, namely ilmenite (FeTiO₃) and silica. The ilmenite obtained from zircon beneficiation has a composition as listed in Table 4.

### Table 4. Composition of Ilmenite from Zircon Beneficiation

| Compound | TiO₂ | Fe₂O₃ | ZrO₂ | Nb₂O₃ | Sn₂O₃ |
|----------|------|-------|------|-------|-------|
| wt, %    | 48.92| 17.02 | 0.90 | 0.69  | 3.47  |

Thus, it was known that the strategic metal that dominates in ilmenite was Ti metal. Then, the separation of Fe from ilmenite sand will produce TiO₂ in high purity.

TiO₂ compounds could be synthesized from ilmenite and rutile. However, rutile needs encouraging efforts to convert into ilmenite as the main source of TiO₂. To produce TiO₂ from ilmenite, several stages of the process were carried out starting with leaching, dilution of leaching results, reduction, hydrolysis, and calcination.

The ilmenite treatment process for obtaining TiO₂ was began with leaching. Leaching is a method of separating solid-liquid or separating certain elements from a solid-solid mixture by using a solvent (leaching agent) that works based on the principle of solubility. The solid phase is contacted with a leaching agent that has a liquid phase to separate the desired solute from the other solid mixture. The
mass transfer was from the solid phase (solute) to the liquid phase so that the separation process could occur.

As 50 grams of ilmenite was leached with 200 mL H\textsubscript{2}SO\textsubscript{4} 50% at 145 °C for 4 hours, the leaching results were diluted with water up to a volume of 750 mL. The result of dilution was filtered, the residue was separated to produce leaching filtrate. The leached filtrate contained TiOSO\textsubscript{4}, Fe\textsubscript{2}(SO\textsubscript{4})\textsubscript{3}, and some impurities that were not deposited in the residual leaching process. So that the titanium hydrate produced was completely white, Fe was separated by reducing Fe\textsubscript{2}(SO\textsubscript{4})\textsubscript{3} to FeSO\textsubscript{4}. It was done by adding Fe powder. Based on the research results, it was known that the more reductions added, the more Fe\textsuperscript{3+} can be reduced to Fe\textsuperscript{2+}, so that the Fe content in the concentrated Ti hydroxide was getting lower.

\[
\begin{align*}
    \text{FeTiO}_3 + 2\text{H}_2\text{SO}_4 & \rightarrow \text{FeSO}_4 + \text{TiOSO}_4 + 2\text{H}_2\text{O} \quad \text{(16)} \\
    \text{Fe}_2(\text{SO}_4)_3 + \text{Fe(s)} & \rightarrow 3\text{FeSO}_4(\text{aq}) \quad \text{(17)}
\end{align*}
\]

The reduction process was done by adding 4 grams of Fe to the leached filtrate. Then it was carried out at 90 °C for 15 minutes. The residue of FeSO\textsubscript{4} and TiOSO\textsubscript{4} crystals were still left in the solution. That solution was hydrolyzed with 5000 mL of water to form precipitated TiO(OH)\textsubscript{2}. The precipitated TiO(OH)\textsubscript{2} was filtered, dried and calcined at 600 °C for 3 hours to get the product of TiO\textsubscript{2} 95.64%.

Figure 4. Process Flow Diagram of TiO\textsubscript{2} from Ilmenite

The obstacle in ilmenite processing lied in high content of Sn and Nb. The high content of the two compounds affected the product purity. Physical optimization of separation needed to be increased so that the Sn and Nb content in ilmenite sand could be as low as possible. Thus, through the further development process of the ilmenite, it is expected that the final product content of TiO\textsubscript{2} can reach 99.9% and an economically valuable side product is obtained.

Titanium, in the form of TiO\textsubscript{2}, as an advanced material has contributed significantly to technological advances. Some sectors that have utilized titanium are health, transportation, industry, and energy. In the health field, titanium is used as an implant and dental prosthesis [29], in transportation used as an aircraft structural material [30], in the industry as a storage tank material and in the energy field as a fuel cell construction material, photocatalytic and sensor [31].
4. Conclusion
The study concluded that the processing and refining of tin tailing mining containing monazite, xenotime, zirconium and ilmenite was able to be carried out. The products have been successfully produced were Ce₂O₃, La₂O₃, concentrated Nd(OH)₃, concentrated Y₂O₃, zircon opacifier, ZrOCl₂, ZrO₂, Zr(SO₄)₂, and TiO₂. These products generally has met the market requirements. However, further process development is still needed especially focusing in the economics concept.

Acknowledgement
Sincere thanks to DIPA CSAT for financial support and also to all staff in process technology division for the support and contribution in this research.

Reference
[1] BMNT, *World Mining Data Report*. 2018.
[2] A. O. Omotehinse and B. D. Ako, “The environmental implications of the exploration and exploitation of solid minerals in Nigeria with a special focus on Tin in Jos and Coal in Enugu,” *J. Sustain. Min.*, vol. 18, no. 1, pp. 18–24, 2019.
[3] W. D. Jackson and G. Christiansen, “International Strategic Minerals Inventory Summary Report - Rare-Earth Oxides,” *U.S. Geol. Surv. Circ. 930-N*, 1993.
[4] Ristekdikti, “Rencana Induk Riset Nasional 2015-2045,” *Kemenristekdikti Republik Indones. Jakarta*, vol. 2045, p. 58, 2016.
[5] P. Data et al., *MINERAL IKUTAN PADA Kajian Potensi Mineral Ikutan*. 2017.
[6] B. Tim LTJ PSTA - PTBGN, “Penyusunan Disain Konsep dan Tekno-ekonomi Pabrik Pengolahan Monasit menjadi Cerium Oksida, Lantanum Oksida dan Konsentrat Neodimium Kapasitas 1000 Ton/ Tahun,” Yogyakarta, 2018.
[7] E. Kim and K. Osseo-Asare, “Aqueous stability of thorium and rare earth metals in monazite hydrometallurgy: Eh-pH diagrams for the systems Th-, Ce-, La-, Nd- (PO₄)-(SO₄)-H₂O at 25 °C,” *Hydrometallurgy*, vol. 113–114, pp. 67–78, 2012.
[8] M. V Purwani and S. Suyanti, “Pengaruh HNO₃ dan KBrO₃ pada Pembuatan Konsentrat Ce, La dan Nd dari Pasir Monasit,” in *Prosiding PPI - PDIPTN 2005*, 2005, no. 2, pp. 194–202.
[9] M. V. Purwani, Suyanti, and A. W. Muhadi, “Ekstraksi Konsentrat Neodimium Memakai Asam di-2-Etil Heksil Fosfat,” *Semin. Nas. IV SDM Teknol. Nukl.*, pp. 439–447, 2008.
[10] N. Panda, N. Devi, and S. Mishra, “Solvent extraction of neodymium(III) from acidic nitrate medium using Cyan 921 in kerosene,” *J. Rare Earths*, vol. 30, no. 8, pp. 794–797, 2012.
[11] F. Xie, T. An, D. Dreisinger, and F. Doyle, “A critical review on solvent extraction of rare earths from aqueous solutions,” *Miner. Eng.*, vol. 56, pp. 10–28, 2014.
[12] M. Mohammadi, K. Forsberg, L. Kloo, J. Martinez De La Cruz, and Å. Rasmuson, “Separation of Nd(III), Dy(III) and Y(III) by solvent extraction using D2EHPA and EHEHPA,” *Hydrometallurgy*, vol. 156, pp. 215–224, 2015.
[13] E. Obón, A. Fortuny, M. T. Coll, and A. M. Sastre, “Hydrometallurgy Mathematical modelling of neodymium , terbium and dysprosium solvent extraction from chloride media using methyltri ( octyl / decyl ) ammonium oleate ionic liquid as extractant,” *Hydrometallurgy*, vol. 173, no. July, pp. 84–90, 2017.
[14] M. V. Purwani and S. Suyanti, “Eksplorium Ekstraksi Pemisahan Neodimium dari Samarium , Itrium dan Praseodimium Memakai Tri Butil Fosfat Separation Extraction of Neodymium from Samarium , Yttrium and Praseodymium Using Tri Butyl Phosphate,” *Eksplorium*, vol. 38, no. 1, pp. 19–28, 2017.
[15] C. K. Gupta and N. Krishnamurthy, *Extractive Metallurgy of Rare Earths*. CRC Press, 2005.
[16] M. Soemarsono and D. Biyantoro, “Pembuatan oksida logam tanah jarang dari umpan hasil dijesti dengan cara pengendapan dan kalsinasi,” in *Prosiding PPI - PDIPTN 2005 Puslitbang Teknologi Maju - BATAN*, 2005, pp. 120–126.
[17] A. Atmawinata, F. Yahya, S. Widhianto, D. Irianto, and A. Adlir, “Telaah penguatan struktur industri pemetaan potensi logam tanah jarang di indonesi,” *Jakarta*, 2014.
[18] D. Biyantoro, “Kajian Pemisahan Mineral Senotim,” Yogyakarta, 2016.
[19] D. Biyantoro, A. Baskoro, and R. Subagiono, “Reaksi dijesti inium dalam pasir senotim,” *Pros. Pertem. dan Present. Ilm. Penelit. Dasar Ilmu Pengetah. dan Teknol. Nukl. P3TM*, pp. 84–89.
2003.

[20] S. Sukmajaya, Isyuniarto, B. Ehb, and I. Prayogo, “Pengaruh Absorbsi La2O3 pada Analisis Pasir Senotim dengan XRF,” Pros. PPI - PDIPTN, pp. 95–104, 2005.

[21] R. J. Weber, “Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues,” United States Environ. Prot. Agency, no. December 31, pp. 1–21, 2012.

[22] United States Department of Energy, “Critical Minerals Strategy,” p. 190, 2011.

[23] B. Sulistyo, “Pembuatan zirkon tetraklorida dari pasir zirkon dengan proses kering secara langsung,” Ganendra, vol. VIII, no. 1, pp. 15–22, 2005.

[24] H. Poernomo, D. Biyantor, and M. V. Purwani, “Kajian Konsep Teknologi Pengolahan Pasir Zirkon Lokal yang Mengandung Monasit, Senotum, dan Ilmenit,” Eksplorium, vol. 37, no. 2, pp. 73–88, 2016.

[25] S. Putra and T. I. Yulianti, “Penentuan waktu pendirian kapasitas produksi pabrik zirkon oksid klorid (ZOC) di Indonesia,” J. Forum Nukl., vol. 7, no. 1, pp. 1–10, 2013.

[26] Sajima and Triyono, “Pelindian Leburan Pasir Zirkon Kalimantan Menggunakan Air Panas Bench Scale,” J. Forum Nukl., vol. 11, pp. 1–6, 2017.

[27] D. Sudjoko and Triyono, “Peningkatan kualitas zirkonia hasil olah pasir zirkon,” Ganendra, vol. XI, no. 1, pp. 11–16, 2008.

[28] E. Susiantini and M. Setyadji, “Pemisahan Zr-Hf dalam Asam Sulfat dengan Resin Penukar Ion,” J. Teknol. Bahan Nukl., vol. 8, no. 2, pp. 67–122, 2012.

[29] H. Koizumi, Y. Takeuchi, H. Imai, T. Kawai, and T. Yoneyama, “Application of titanium and titanium alloys to fixed dental prostheses,” J. Prosthodont. Res., 2019.

[30] I. Inagaki, Y. Shirai, T. Takechi, and A. Nozomu, “Application and Features of Titanium for the Aerospace Industry,” 2014.

[31] M. Abdullah and S. K. Kamarudin, “Titanium dioxide nanotubes (TNT) in energy and environmental applications: An overview,” Renew. Sustain. Energy Rev., vol. 76, no. November 2016, pp. 212–225, 2017.