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# Economic analysis of the processing of various titanium-containing raw materials to obtain titanium, vanadium, and niobium

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**Abstract.** This work presents an economic analysis of processing various titanium-containing raw materials-titanium slag and synthetic rutile-through chlorination in a molten salt medium in the presence of carbon. The processing of titanium-containing raw materials is carried out using a chlorination technology in molten alkali metal salts ($MgCl_2$, NaCl, KCl) with high-concentration gaseous chlorine in the presence of a carbon-containing reducing agent. Anthracite is used as the reducing agent, while waste sludge from magnesium electrolysis is used as the molten medium. The processing takes place in cylindrical chlorination furnaces lined with fireclay bricks at temperatures of 720-800°C. The chlorination products are directed to a condensation system. The work provides a description of the Satpayev ilmenite deposit in East Kazakhstan and presents the chemical composition of Satpayev ilmenite concentrate, titanium slag, and synthetic rutile obtained through various processes. A correlation is established between the vanadium, niobium, and tantalum content in ilmenite concentrates and their prevalence in the Earth's crust. Based on this correlation, the order of transition metals in Group V of the periodic table is determined according to their decreasing concentration in the concentrates. Technological challenges associated with processing titanium-containing raw materials with elevated levels of certain components are described, along with some methods for producing synthetic rutile. A cost comparison is provided for the production of titanium slag and synthetic rutile. Material balance calculations for the chlorination process of titanium slag and synthetic rutile from different production methods are performed to assess raw material costs and waste disposal expenses. The study concludes that producing synthetic rutile from Satpayev ilmenite concentrate is economically feasible.

***Keywords:*** *slag, rutile, costs, processing, chlorination, waste*.

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## 1. Introduction

Ilmenite is the most important raw material source for the global titanium industry. Large ilmenite deposits are found in India (Kerala, Ceylon), the USA (Florida), Brazil, Russia, Ukraine, and other countries [1]. The physicochemical and mineralogical properties of ilmenite are well studied [2,3]. Various methods exist for enriching and processing ilmenite, including direct reduction methods [4]. However, the most common method is reductive ore-thermal smelting, which produces a titanium-enriched product-titanium slag and pig iron, which is used in industrial enterprises. An alternative method for processing ilmenite concentrate is thermochemical treatment to produce synthetic rutile. Examples include the sulfiding process and carbothermal reduction [5].

In the Republic of Kazakhstan, three titanium-zirconium sand deposits have been developed in the Aktobe (Shokash), Akmola (Obukhov), and East Kazakhstan (Satpayev-Bektimir) regions [6]. The Satpayev deposit has been prioritized as the most promising and the closest to the processing plant. This deposit is located 200 km from Ust-Kamenogorsk.

The Satpayev ilmenite placer was discovered in 1989 during preliminary geophysical and geochemical studies. It was formed by the reworking of the ore-bearing weathering crust of the Karaotkel deposit [7]. The placer is located in the southwestern frame of the Preobrazhensky granitoid massif of the Buransky complex. Subordinate rock formations include the Maksut gabbroids and the Kunush granites, with fragmentary outcrops of the Bukon and Maitubin suites also noted [8].

The placer is of alluvial origin, with a productive sand-clay horizon of presumed pre-Neogene age lying on weathered crusts or bedrock [8]. The deposit consists of three alluvial (buried) placers of Oligocene age [7]. The channel width varies from 100 to 650 meters, the total explored length is 7,250 meters, and the thickness of ore sands ranges from 4 to 11 meters. The ore minerals are primarily ilmenite (90-97%) and zircon, with occasional occurrences of rutile, anatase, and leucoxene. The average ilmenite content in ore-bearing horizons is 151 kg/m$^3$. The balance reserves of the placer are as follows: ore sands – 12,053 thousand m$^3$, ilmenite-1,821 thousand tons [8].


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## 2. Materials and methods

The ilmenite concentrates from the Satpayev deposit, as a raw material for titanium slag production with subsequent processing using chloride technology, has several significant drawbacks, including high levels of iron and silicon oxides. However, one advantage of this raw material is its relatively low vanadium content and the presence of rare-earth elements (vanadium, scandium, niobium) that can be extracted as by-products.

A comparison of ilmenite compositions from different sources revealed that the most significant difference between the Vilnohirsk (Ukraine) ilmenite concentrate and the one from Kazakhstan is the higher degree of weathering of the Ukrainian ores, as indicated by the almost complete absence of $Fe^{2+}$. This is likely the reason for the lower vanadium and niobium content, indirectly suggesting that niobium and tantalum were initially associated with $Fe^{2+}$ but were lost during geological transformations.

Spectral analysis of the chemical composition of the initial titanium-containing materials showed that the Vilnohirsk ilmenite concentrate contains nearly 1.7 times more vanadium pentoxide and 1.6 times more niobium pentoxide than the Kazakhstani concentrate.

A correlation has been established between the content of vanadium, niobium, and tantalum in ilmenite concentrates and their abundance in the Earth's crust, in weight percent:

– V – $2.0 \times 10^{-2}$;

– Nb – $3.2 \times 10^{-5}$;

– Ta – $2.4 \times 10^{-5}$l

It should be noted that vanadium group elements form the most stable compounds in the pentavalent state, as they achieve a stable electron configuration with eight electrons after losing five from their outermost and penultimate orbitals. As the atomic number increases, the tendency of these elements to exhibit valency lower than five decreases.

According to the identified pattern, the transition metals of Group V (secondary subgroup) in the periodic table are arranged in the following order based on their decreasing concentration in the ilmenite concentrates:

$V_2O_5 > Nb_2O_5 > Ta_2O_5$.

Vanadium, niobium, and tantalum, considering their fractional percentage content, are present in ilmenite concentrates as isomorphic impurities in titanium minerals.

Scanning electron microscopy (SEM) of localized surface areas of polished sections from the Obukhov ilmenite concentrate has provided micrographs that illustrate the morphology, association characteristics, and elemental composition of mineral aggregates and individual mineral grains. These micrographs reveal isomorphic vanadium impurities in rutile and leucoxene grains, where vanadium replaces trivalent iron ions during the natural decomposition of ilmenite.

Isomorphic impurities of niobium and tantalum in titanium minerals, as well as rare-earth elements from the cesium and yttrium groups present in the Obukhov ilmenite concentrate (OIC), were not detected due to their low concentration and the insufficient resolution of our JEOL JXA-8230 scanning electron microanalyzer from the Japanese company JEOL.

## 3. Results and discussion

Below are micrographs of rutile and leucoxene grains from the Obukhov ilmenite concentrate with isomorphic vanadium impurities (Figure 1). Further below, Table 1 presents the results of the balance distribution and extraction analysis of titanium, iron, vanadium, and niobium in the products of reductive electro-smelting of charge mixtures from the Vilnohirsk and Satpayev ilmenite concentrates with anthracite. Table 2 provides the chemical composition of the Satpayev ilmenite concentrate.

Due to the high content of iron oxides in the pyrometallurgical smelting of the Satpayev ilmenite concentrate, the following challenges arise:

– increased cost of titanium slag due to higher consumption of electrical energy, carbon-containing reductant, and electrodes;

– furnace clogging with accretions, leading to a reduction in the furnace bath volume and decreased productivity;

– exposure of the furnace lining in the upper part of the bath.

As a result of these challenges, titanium slag production is carried out using a mixture of ilmenite concentrates from the Satpayev (Kazakhstan) and Vilnohirsk (Ukraine) deposits in various proportions. The most technologically and economically optimal ratios are Vilnohirsk/Satpayev – 60/40% and 65/35%.

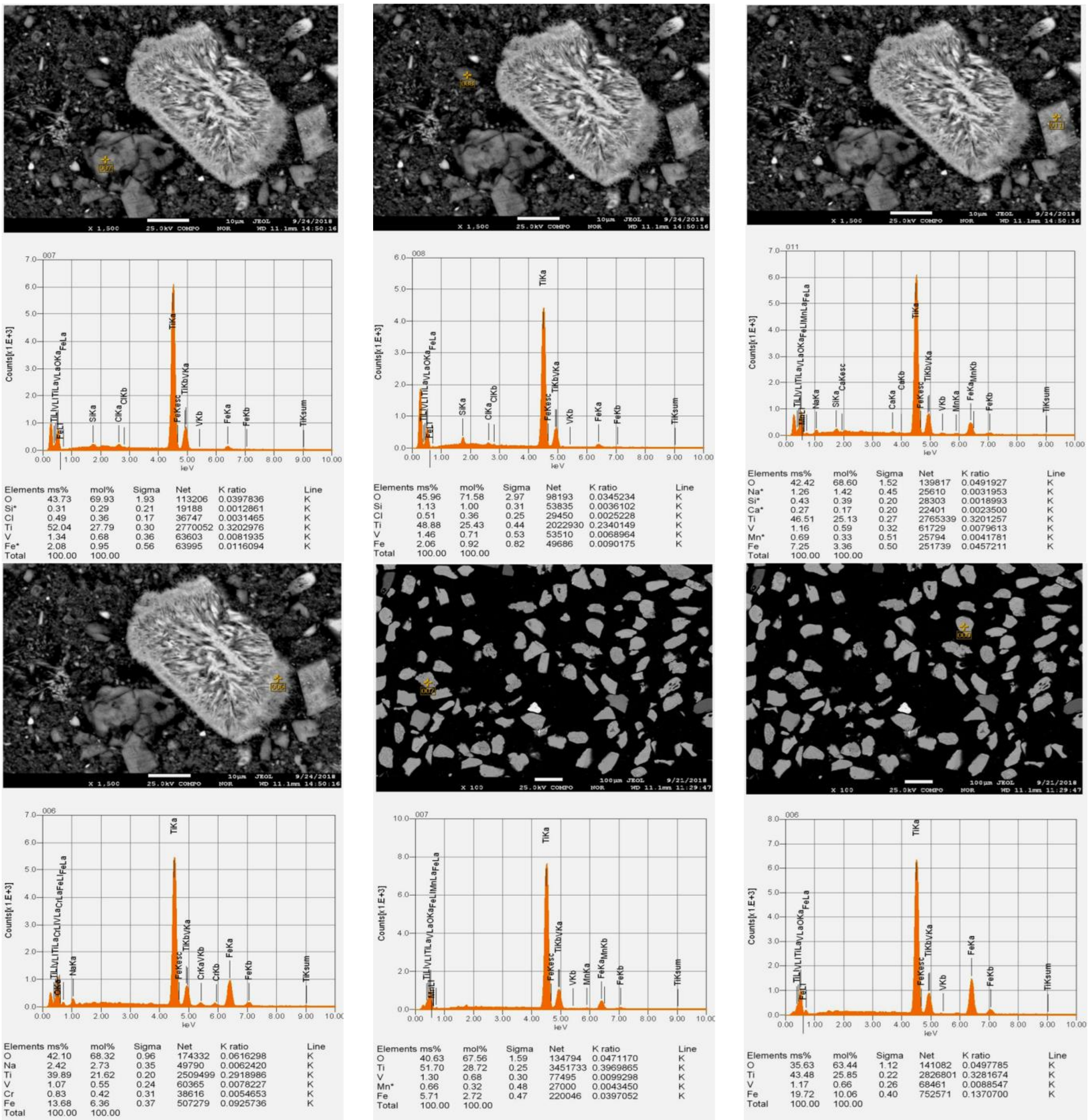
At the same time, several technologies for producing synthetic rutile from ilmenite concentrate have been developed and are mainly applied abroad: Becher process (Australia), Oceanic process (Canada), Chlorine process (Australia), NewGenSR process (Finland-Australia), Mintek process (South Africa), Murso process (Australia-Japan), Tiomin (TSR) process (Canada), Heubach process (Germany), Austpac ERMS/EARS process (Australia) [4], Mitsubishi process (Japan), SREP process (Australia), Western Titanium process (Australia), Dhrangadhra process (India), Benilite process (USA), Ishihara Sangyo process (Japan) [10].

***Table 1. Distribution of titanium, iron, vanadium, and niobium among the products of ilmenite concentrate processing***

| Product names | Content, % | | | | Extraction, % | | | |
|---|---|---|---|---|---|---|---|---|
| | $TiO_2$ | FeO | $V_2O_5$ | $Nb_2O_5$ | $TiO_2$ | FeO | $V_2O_5$ | $Nb_2O_5$ |
| Titanium slag | 86.214 | 6.355 | 0.383 | 0.0438 | 97.803 | 16.166 | 84.891 | 99.984 |
| Gas cleaning dust | 43.40 | 36.00 | 0.275 | 0.0325 | 1.968 | 2.506 | 2.436 | 3.373 |
| Flue gas dust | 36.90 | 24.65 | 0.11 | 0.02 | 0.014 | 0.030 | 0.007 | 0.016 |
| Master alloy | Ti | Fe | V | Nb | Ti | Fe | V | Nb |
| | 0.012 | 96.98 | 0.02 | - | 0.005 | 69.50 | 1.734 | - |
| Work-in-Progress (WIP) Product | - | - | - | - | 2.178 | 14.304 | 13.368 | - |
| Total: | - | - | - | - | 100 | 100 | 100 | 100 |

***Table 2. Chemical composition of the Satpayev ilmenite concentrate***

| Component | $SiO_2$ | $TiO_2$ | $Fe_2O_3$ | $Al_2O_3$ | $Cr_2O_3$ | CaO | MgO | MnO | $V_2O_5$ | $P_2O_5$ | S | $ZrO_2$ | $Sc_2O_3$ | $Ta_2O_5$ | $Nb_2O_5$ | Act. (Bq/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % | 0.91 | 52.98 | 41.87 | 0.33 | 0.31 | 0.27 | 0.41 | 2.9 | 0.2 | 0.17 | 0.035 | 0.16 | 0.002 | 0.002 | 0.02 | 1236.5 |




(a) (b) (c)

***Figure 1. Micrographs of rutile and leucoxene grains from the Obukhov ilmenite concentrate with isomorphic vanadium impurities: (a) – associates of leucoxene grains; (b) – rutile grain; (c) – leucoxene grain***

There are several industrial methods for obtaining synthetic rutile or high-quality titanium slag from ilmenite as a raw material for chloride processes [11]. These processes involve a combination of thermal oxidation and reduction through roasting, leaching, and physical separation. Iron is converted into soluble divalent or elemental forms by reduction at high temperatures, followed by acid leaching to obtain synthetic rutile ($TiO_2$).

The industrial method of processing ilmenite into synthetic rutile is typically represented by the Becher process. Ilmenite contains 40-65% titanium in the form of $TiO_2$, with the remaining portion consisting of iron oxide. In the Becher process, iron oxide is removed, leaving behind synthetic rutile containing more than 90% $TiO_2$. The technological scheme includes four main stages: oxidation, reduction, aeration, and acid leaching.

Oxidation involves heating ilmenite in a rotary kiln with air to convert the iron in ilmenite into iron oxides:

$$4FeTiO_{3(s)} + O_{2(g)} \rightarrow 2Fe_2O_3{\cdot}TiO_{2(s)} + 2TiO_{2(s)}.$$

This allows for the utilization of a wide range of ilmenite materials with various forms of iron (II) and iron (III) for further processing. The reduction process is carried out in a rotary kiln with pseudobrookite ($Fe_2O_3{\cdot}TiO_2$), a mixture of coal and sulfur at temperatures above 1200°C to reduce iron oxide to metallic iron:

$$Fe_2O_3{\cdot}TiO_{2(s)} + 3CO_{(g)} \rightarrow 2Fe_{(s)} + 2TiO_{2(s)} + 3CO_{2(g)}.$$

Metallic iron is oxidized and precipitates from the solution as sludge during the aeration stage, known as «rust removal», in large tanks containing a 1% ammonium chloride solution at a temperature of 80°C. Then, the finer iron oxide is separated from the larger synthetic rutile particles.

$4Fe_{(s)} + 3O_{2(g)} \rightarrow 2Fe_2O_3$.

After the majority of iron oxide is removed, the residual iron oxide is leached using 0.5 M sulfuric acid and separated from the synthetic rutile.

In another industrial process, the Benelite process, thermal reduction with carbon is used to convert other forms of iron into divalent iron, which is then separated through leaching with an 18–20% HCl solution.

The Murso process employs fluidized beds for thermal transformations, where ilmenite undergoes pre-oxidation in a fluidized bed at 900-950°C. The hot oxidized ore is then transferred to another fluidized bed, where iron ions are reduced using a reductant (such as gaseous $H_2$). The product from the second fluidized bed is subsequently leached with approximately 20% HCl at 108-110°C. The remaining hydrochloric acid is regenerated after the magnetic separation of solid synthetic rutile from the leach solution.

In the Laporte process, the ore is pre-oxidized in a fluidized bed at around 950°C, followed by reduction roasting in a rotary kiln using coal as the reductant. Incomplete reduction of iron to the divalent state without metallization is achieved through proper selection of equipment, temperature, and reductant. The partial pressure of $CO_2$ generated during the reaction is sufficient to prevent the formation of metallic iron.

$CO_{2(g)} + Fe_{(s)} = FeO_{(s)} + CO_{(g)}$.

The reactivity of the roasted ore is so high that a single-stage leaching with an 18% HCl solution at atmospheric pressure for 3.5 hours is sufficient to produce a product with the same overall particle size distribution as the original ore. A contact filter is used during leaching to prevent the formation of very fine particles from the soft material. It is claimed that the discharged ore does not contain fine $TiO_2$ particles.

Reduction roasting, in which the iron content in ilmenite is reduced to divalent forms followed by sulfuric acid leaching, is used in the Kataoka process in Japan. In this process, hydrated titanium dioxide is added to the leach solution as seeds to increase the rate of titanium salt precipitation and improve the leaching efficiency and iron removal. This also allows iron to be extracted from the ore at lower temperatures and lower sulfuric acid concentrations, making the reactor design more economical. More than 95% of the $TiO_2$ content in ilmenite can be recovered.

While most synthetic rutile processes yield products containing 93% $TiO_2$, the Austpac process produces synthetic rutile with 97% $TiO_2$. Ilmenite ore is roasted at 800-1000°C to selectively magnetize ilmenite so that gangue minerals can be easily removed through magnetic separation. Roasting also activates the iron-bearing component of ilmenite, enhancing iron leaching. Iron and other impurities are removed by leaching with 25% (by mass) HCl. The resulting solids are then filtered, washed, and calcined. The product undergoes magnetic separation at the final stage, yielding synthetic rutile containing 97% $TiO_2$.

In the Dunn process, an alternative thermal conversion method has been proposed. The principle of the selective chlorination process is that iron in ilmenite chlorinates more easily than titanium. The excess ilmenite in the fluidized bed prevents titanium chlorination since any chlorinated titanium reacts with iron oxide to form titanium dioxide. The gaseous iron chloride exiting the fluidized bed reacts with oxygen to form $Fe_2O_3$ and $Cl_2$ gas for reuse, as described in the following equation:

$4FeCl_{3(g)} + 3O_{2(g)} = 2Fe_2O_{3(s)} + 6Cl_{2(g)}$.

The reactivity of ilmenite ore during hydrochloric acid leaching was significantly enhanced by the reduction of metallic iron in the solution. It was proven that adding a small amount of iron powder (0.1 kg of iron powder per 1 kg of ilmenite ore) significantly increased the leaching rate of both iron and titanium. When the solid-to-liquid ratio was increased from 1/20 to 1/8, complete dissolution of iron and titanium was achieved in 1.5 hours with the addition of iron powder, compared to 2.5 hours under similar leaching conditions without iron powder.

The direct leaching process for upgrading Rosetta ilmenite concentrate (40-47% $TiO_2$) into synthetic rutile without a thermal treatment stage was investigated by Lashin (2005). A high acid concentration (a high molar ratio of ilmenite to acid) and reduction by metallic iron facilitated the removal of iron from the mineral lattice while preventing titanium dissolution. Without the addition of a reducing agent, the iron leaching efficiency did not exceed approximately 55% when using concentrated HCl (12 M) with a solid-to-liquid ratio of 1:5 at 90°C for 8 hours, while titanium remained almost completely undissolved. The addition of metallic iron increased the titanium recovery to 89% $TiO_2$. Clearly, a reducing agent is necessary to convert Fe(III) into the more soluble Fe(II) form. The remaining total iron content of less than 7% $Fe_2O_3$ is likely due to the complex mineralogical composition, influenced by the presence of three main groups of solid solutions in the $FeO–Fe_2O_3–TiO_2$ ternary system:

– $FeO \cdot Fe_2O_3–Fe_2TiO_4$: magnetite–ulvospinel series;
– $Fe_2O_3 \cdot FeTiO_3$: hematite–ilmenite series;
– $Fe_2TiO_5–FeTi_2O_5$: pseudobrookite series.

As seen in Table 3, synthetic rutile obtained by any of the processes surpasses titanium slag in $TiO_2$ content and has a lower Fe content while retaining $V_2O_5$ and $Nb_2O_5$ for further by-product extraction.

Literature [9] provides data comparing the production costs of synthetic rutile and titanium slag using various technologies (Table 4). From Table 4, it can be seen that the costs and production expenses for titanium slags are higher compared to synthetic rutile production processes.

In this work, an attempt is made to further analyze the economic feasibility of processing synthetic rutile and titanium slag using chloride technology. The analysis is based on calculating the material balance of the chlorination process when processing different raw materials (with varying $TiO_2$ and FeO content), determining the consumption of raw materials, main reagents, and waste generation volumes. Accordingly, the economic costs of processing each type of titanium-containing raw material are compared.

The calculation of material balances was performed in MS Excel using the methodology presented in the literature [11]. In the calculations, finely ground anthracite with the following composition (%) is used as a reducing agent: 93.45 C; 3.52 volatiles; 2.33 ash; 0.7 S; 0.1 $H_2O$. Chlorination is carried out using anodic chlorine gas with the addition of evaporated chlorine, with a total mass concentration of ~96%.

***Table 3. Chemical composition of synthetic rutile obtained by different processes [10] compared to titanium slag (60/40% Vilnohirsk / Satpayev)***

| Process / Component | Titanium slag 60/40 Vilnohirsk / Satpayev | Ishihara Sangyo process | Bemilite process | Dhrangadhra process | Western titanium process | Becher process | SREP process | Mitsubishi process | Summit process | Murso process | Clorine technology process |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $TiO_2$ | 86.0 | 96.1 | 93.0 | 90-92 | 92.0 | 92.5 | 92-95 | 96.7 | 94.0 | 96.2 | 97.5 |
| Fe(total) | - | - | 2.0 | 3.0 | 3.6 | 2.4 | 1.0-3.0 | - | - | - | 0.46 |
| FeO | 6.6 | - | - | - | - | - | - | - | 2.0 | - | - |
| $Fe_2O_3$ | - | 1.3 | - | - | - | - | - | 0.4 | - | 1.5 | 0.66 |
| $Cr_2O_3$ | 0.7 | 0.15 | 0.04 | 0.2 | - | 0.10 | 0.2-0.3 | - | 0.10 | 0.15 | 0.11 |
| $Al_2O_3$ | 2.3 | 0.46 | 0.42 | 1.0 | 0.7 | 1.1 | 0.5-0.8 | 0.7 | 1.7 | 0.2 | 0.49 |
| $V_2O_5$ | 0.3 | 0.20 | 0.06 | 0.25 | 0.12 | 0.22 | 0.25 | - | 0.15 | 0.04 | 0.04 |
| $Nb_2O_5$ | 0.1 | 0.25 | 0.6 | - | - | 0.25 | 0.3 | - | - | - | 0.07 |
| $Ta_2O_5$ | 0.02 | - | - | - | - | - | - | - | - | - | - |
| $Sc_2O_3$ | 0.02 | - | - | - | - | - | - | - | - | - | - |
| $P_2O_5$ | - | 0.17 | - | 0.2 | - | 0.03 | 0.01 | - | 0.1 | - | 0.072 |
| MnO | 2.0 | 0.03 | 0.22 | 0.1 | 2.0 | 1.1 | 0.8-1.2 | 0.06 | 1.7 | 0.05 | <0.01 |
| MgO | 0.9 | 0.07 | 0.05 | 0.05 | 0.15 | 0.30 | 0.3 | - | - | 0.04 | 0.027 |
| CaO | 0.5 | 0.01 | - | 0.05 | 0.03 | 0.03 | 0.07-0.15 | - | 0.7 | - | 0.065 |
| $ZrO_2$ | 0.2 | 0.15 | 0.12 | 1.0 | - | 0.2 | 0.1 | - | 0.2 | - | 0.19 |
| $SiO_2$ | 3.0 | 0.5 | 1.6 | 1.5 | 0.7 | 0.9 | 0.8-1.2 | 0.1 | 0.5 | - | 0.46 |
| $SnO_2$ | - | - | 0.14 | - | - | - | - | - | - | - | 0.003 |
| As | - | - | - | - | - | - | - | - | - | - | - |
| S | 0.02 | 0.01 | 0.01 | - | 0.15 | 0.2 | 0.03 | - | 0.02 | - | 0.006 |
| C | - | - | - | - | 0.15 | - | - | - | - | - | 0.09 |
| U | - | - | - | - | - | ~10 ppm | 10 ppm | - | - | - | - |
| Th | - | - | - | - | - | 80-450 ppm | 80-90 ppm | - | - | - | - |

***Table 4. Comparative analysis of the production cost of synthetic rutile and titanium slags using different technologies***

| Processes | $TiO_2$, % | Capital costs, $/t | Operating cost, $/t | Product price, $/t |
|---|---|---|---|---|
| ERMS | >97 | 450 | 140 | 420 |
| Becher | >90 | 550 | 150 | 350 |
| Benilite | >93 | 750 | 280 | 380 |
| Titania Slag | >85 | 970 | 190 | 300 |
| Ti-slag 60/40 Voln./Satp | >85 | - | - | 801.6 |

To maintain an acceptable viscosity of the working melt in the chlorinator, spent electrolyte with the following composition (%) is used: 76 KCl; 15.5 NaCl; 2.7 $CaCl_2$; 5.5 $MgCl_2$; 0.02 MgO; 0.04 $Fe_2O_3$; 0.07 $Al_2O_3$; 0.07 $SiO_2$; 0.1 others. The electrolyte feed depends on the FeO content in the titanium-containing raw material and is as follows:

– for 7-9% FeO – 120 kg/t $TiCl_4$;
– for 4-5% FeO – 110 kg/t $TiCl_4$;
– for 2-3% FeO – 100 kg/t $TiCl_4$.

The results of the calculation are shown in Table 5.

***Table 5. Results of material balance calculations for chlorination***

| Material | $TiO_2$, % | FeO, % | Specific consumption per 1 ton of $TiCl_4$, kg | | | | Specific formation per 1 ton of $TiCl_4$, kg | | Specific material costs, $/t | Specific costs for waste utilization, $/t |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Slag/rutile | Reduc. agent | Cl | Elect. | $TiCl_4$ slag waste | Waste gases | | |
| Ti-slag 60/40 Voln/Satp. | 86 | 6.6 | 537.6 | 96 | 975.3 | 120 | 92.7 | 324.3 | 99 476 | 21 597 |
| Syn. rutile Becher process | 92.5 | 3.65 | 496.8 | 87.9 | 891.6 | 110 | 56.1 | 296.9 | 90 966 | 17 609 |
| Syn. Rutile Western Titanium Process | 92 | 4.13 | 499.6 | 87.9 | 891.4 | 110 | 62.8 | 296.8 | 90 949 | 18 108 |
| Syn. Rutile Dhrangadhra Process | 92 | 5.04 | 500 | 88.9 | 900.5 | 110 | 47.7 | 300.4 | 91 870 | 17 135 |
| Syn. Rutile Ishihara Sangyo Process | 96.1 | 2.62 | 477.4 | 85.7 | 863.2 | 100 | 37.5 | 289.2 | 88 028 | 15 863 |
| Syn. Rutile Summit Process | 94 | 2 | 488.9 | 88 | 885.4 | 100 | 58.1 | 296.9 | 90 256 | 17 759 |
| Syn. Rutile SREP Process | 93.5 | 3.11 | 491.4 | 87.6 | 884.3 | 100 | 51.9 | 295.9 | 90 103 | 17 248 |
| Syn. Rutile Chlorine Technology Process | 97.5 | 1.4 | 470.3 | 84.9 | 852.7 | 100 | 34.9 | 286.4 | 87 018 | 15 541 |

The calculation is based on 1000 kg of processed titanium slag or synthetic rutile, with results presented per 1 ton of produced $TiCl_4$. The obtained results indicate that the specific costs of the chlorination process directly depend on the quality of the processed titanium-containing raw material. The higher the $TiO_2$ content and the lower the FeO content, the lower the processing costs.

It should be noted that the results of the material balance calculations are theoretical in nature and slightly underestimated compared to practical data, as the calculations are based on 1 ton of $TiCl_4$ obtained in a vapor-gas mixture, without accounting for $TiCl_4$ losses during condensation. According to the author's estimates, the error does not exceed 4%. However, in the author's opinion, the obtained results make it possible to conduct an economic analysis of processing various titanium-containing raw materials using chlorination in a molten alkali metal salt medium in the presence of carbon.

## 4. Conclusions

Thus, from an economic standpoint, the processing of synthetic rutile compared to titanium slag is more feasible and retains the possibility of extracting rare earth elements such as vanadium and niobium as by-products. This analysis allows for considering the possibility of establishing a production stage for synthetic rutile from the Satpayev ilmenite concentrate at titanium manufacturing enterprises.

### Author contributions

Conceptualization: T.K.S., T.A.C.; Data curation: E.S.M.; Formal analysis: T.K.S., E.S.M.; Funding acquisition: T.K.S., T.A.C.; Investigation: T.K.S., T.A.C.; Methodology: E.S.M.; Project administration: T.K.S., E.S.M.; Resources: E.SM..; Software: E.S.M.; Supervision: T.K.S., T.A.C.; Validation: E.S.M.; Visualization: E.S.M.; Writing – original draft: T.K.S., E.S.M.; Writing – review & editing: T.A.C. All authors have read and agreed to the published version of the manuscript.

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### Conflicts of interests

The authors declare no conflict of interest.

### Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

### References

[1] Zwierynski, A.J., Zlotkowski, A., Solecki, M. L., Balicki, R., Binkowska, W., Janiak, A., Edelmüller, H., Gardynik, A. & Leśniowska M. (2022). Ilmenite, the raw material of the future. *Mathematical methods and terminology in geology*, 69-74

[2] Mehdilo, A., Irannajad, M. & Rezai B. (2015). Chemical and mineralogical composition of ilmenite: Effects on physical and surface properties. *Minerals Engineering*, (70), 64-76. https://doi.org/10.1016/j.mineng.2014.09.002

[3] Schmidt, R. (2019). Magnetic properties of ilmenite $Mn_2FeSbO_6$. *Journal of Magnetism and Magnetic Materials*, (480), 58-63. https://doi.org/10.1016/j.jmmm.2019.02.047

[4] Wei, Lu, Xuewei, Lu, Junyi, Xiang, Kai, Hu, Shiqing, Zhao, Jie, Dang, Kexi, Han & Bing, Song. (2019). Effect of preoxidation on the reduction of ilmenite concentrate powder by hydrogen. International *Journal of Hydrogen Energy*, *44*(2) 4031-4040, https://doi.org/10.1016/j.ijhydene.2018.12.139

[5] Subasinghe, H.C.S., Ratnayake, A.S. (2021). Processing of ilmenite into synthetic rutile using ball milling induced sulphurisation and carbothermic reduction. *Minerals Engineering*, (173), 107197. https://doi.org/10.1016/j.mineng.2021.107197

[6] Kurmangaliyev, A.A. (2005). Current state and development trends of the raw material base of the titanium-magnesium industry in the Republic of Kazakhstan. *Geology, Mining, Metallurgy. Bulletin of VKGTU*, (4), 13-20.

[7] Dyachkov, B.A., Mochalkina, L.N., Kuzmina, O.N., Bochkova, O.I. & Kravchenko M.M. (2005). Types of weathering crust deposits in Eastern Kazakhstan. *Geology, Mining, Metallurgy. Bulletin of VKGTU*, (4), 6-12.

[8] Kravchenko, M.M., Dyachkov, A.A., Suiekpaev, E.S., Sapargaliyev, E.M., Azelkhanov, A.Zh., Oitseva, T.A. (2016). Prospects for strengthening and developing the raw material base of titanium production in Eastern Kazakhstan. *Geology. Bulletin of Perm University*, (1), 82-90.

[9] Zabolotskaya, Y.V. (2014). Autoclave de-siliconization of leucoxene concentrate with calcium hydroxide to obtain synthetic rutile (doctoral dissertation). *Moscow*

[10] Harald Elsner. (2010). Heavy Minerals of Economic Importance. *BGR, Hannover, Germany*

[11] Zhang, W., Zhu, Zh. & Cheng, Ch.Y. (2011). A literature review of titanium metallurgical processes. *Hydrometallurgy*, (108), 177-188. https://doi.org/10.1016/j.hydromet.2011.04.005

[12] Nadolsky, A.P. (1980). Calculation of processes and apparatus for refractory metal production. *Moscow: Metallurgy.*

# Титан, ванадий және ниобий алу арқылы құрамында титан бар әр түрлі шикізатты өңдеудің экономикалық талдауы

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**Аңдатпа.** Жұмыста әртүрлі титан бар шикізатты-титан қожын және синтетикалық рутил – көміртектің қатысуымен балқытылған тұзды ортада хлорлау әдісімен өңдеудің экономикалық талдауы ұсынылған. Құрамында титан бар шикізатты қайта өңдеу құрамында көміртегі бар тотықсыздандырғыштың қатысуымен жоғары концентрацияланған хлор газымен балқытылған сілтілі металл тұздарында ($MgCl_2$, NaCl, KCl) хлорлау технологиясы бойынша жүзеге асырылады. Тотықсыздандырғыш ретінде антрацит, балқытылған орта ретінде магний электролизінің үйінді шламы қолданылады. Қайта өңдеу шамот кірпішпен қапталған цилиндрлік хлорлау пештерінде 720-800°C температурада жүзеге асырылады. Жұмыста Шығыс Қазақстандағы Сәтбаев ильменит кен орнының сипаттамасы берілген, әртүрлі тәсілдермен алынған Сәтбаев ильменит концентратының, титан қожының және синтетикалық рутил химиялық құрамы ұсынылған. Ильменит концентраттарындағы ванадий, ниобий және тантал құрамы мен олардың жер қыртысында таралуы арасында корреляция орнатылған. Осы корреляция негізінде элементтердің периодтық жүйесінің V тобындағы өтпелі металдардың реті олардың концентраттардағы концентрациясы төмендеген сайын анықталады. Құрамында титан бар шикізатты кейбір компоненттердің жоғарылауымен өңдеуге байланысты технологиялық қиындықтар, сондай-ақ синтетикалық рутил алудың кейбір әдістері сипатталған. Титан қожы мен синтетикалық рутил өндірісінің құнын салыстыру келтірілген. Шикізат шығындары мен қалдықтарды кәдеге жарату шығындарын бағалау үшін титан қожын хлорлау процесінің материалдық балансы мен өндірістің әртүрлі әдістерінің синтетикалық рутил есептеулері жүргізілді. Зерттеуде Сәтбаев кен орнының ильменит концентрат синтетикалық рутил өндірісі экономикалық тұрғыдан тиімді деген қорытындыға келді.

***Негізгі сөздер:*** *қож, рутил, шығындар, қайта өңдеу, хлорлау, қалдықтар*.

# Экономический анализ переработки различного титансодержащего сырья с получением титана, ванадия и ниобия

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**Аннотация.** В работе представлен экономический анализ переработки различного титансодержащего сырья – титанового шлака и синтетического рутила – методом хлорирования в расплавленной солевой среде в присутствии углерода. Переработка титансодержащего сырья осуществляется по технологии хлорирования в расплавленных солях щелочных металлов ($MgCl_2$, NaCl, KCl) высококонцентрированным газообразным хлором в присутствии углеродсодержащего восстановителя. В качестве восстановителя используется антрацит, в качестве расплавленной среды – отвальный шлам электролиза магния. Переработка осуществляется в цилиндрических печах хлорирования, футерованных шамотным кирпичом, при температурах 720-800°C. Продукты хлорирования направляются в конденсационную систему. В работе дано описание Сатпаевского месторождения ильменита в Восточном Казахстане, представлен химический состав Сатпаевского ильменитового концентрата, титанового шлака и синтетического рутила, полученных различными способами. Установлена корреляция между содержанием ванадия, ниобия и тантала в ильменитовых концентратах и их распространенностью в земной коре. На основании этой корреляции определен порядок переходных металлов в V группе периодической системы элементов по мере убывания их концентрации в концентратах. Описаны технологические сложности, связанные с переработкой титансодержащего сырья с повышенным содержанием некоторых компонентов, а также некоторые способы получения синтетического рутила. Приведено сравнение себестоимости производства титанового шлака и синтетического рутила. Проведены расчеты материального баланса процесса хлорирования титанового шлака и синтетического рутила различных способов производства для оценки затрат на сырье и затрат на утилизацию отходов. В исследовании сделан вывод о том, что производство синтетического рутила из концентрата ильменита Сатпаевского месторождения экономически целесообразно.

***Ключевые слова:*** *шлак, рутил, затраты, переработка, хлорирование, отходы*.

**Publisher’s note**