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Review paper

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Russian zirconium industry: current issues in raw material supply

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Abstract
The relevance of the research is connected with Russia's long-term import dependence on zirconium raw materials.
Goal of this research: to study the dynamics of commodity flows (production, import, export, consumption) of Russian zirconium raw materials; its prices (world and Russian); the raw material base of zirconium in Russia and the prospects for national production of its extraction and processing.
Methods: statistical, graphic, logical.
Results: Russia imports the vast majority (3.5–14.9 kt/year or 98–100 % of consumption) of consumed zircon concentrate. At the same time, almost all of the baddeleyite mined in Russia (4.0–9.3 kt/year or (96–100 % of production) is exported. Since 2018 has there been a decrease in its export supplies and an increase in the national consumption (up to 60 % of production).
Russia has existing deposits, including a useful zirconium component, but all are connected with a certain economic and technological complexity in their development.
In 2022, the national production of selective zircon concentrate began during the development of the Tugan titanium-zirconium deposit. This deposit covers up to 30 % of Russia's demand for zirconium raw materials up to 2023. Furthermore, the construction of the 2-nd stage of the Tugan mining and processing plant will increase its supply to 15 kt/year. This will completely cover Russian demand for zirconium raw materials. Work is in progress on Zashikhinsky field preparation, where, in the course of enrichment of tantalum-rare-earth ores, up to 8 kt/year of zircon concentrate will be additionally extracted. The emerging trend of reducing Russia's import dependence on zirconium raw materials, and in the future its complete elimination will allow consumption of zircon and zirconium oxides to be increased in the most demanding area of their use – for dampening the glaze of ceramic tiles. The presence of an independent and sufficient national mining base of zirconium raw materials will allow Russian production of metal zirconium, zirconium refractory and abrasive products, solid fuel energy cells and other zirconium-containing applications to be developed.

Keywords
strategic raw materials, import dependence, zircon, baddeleyite, metal zirconium, zirconium oxides, export, national projects

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ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Обзорная статья

Обзор циркониевой отрасли России: состояние, проблемы обеспечения сырьем

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Аннотация

Актуальность работы обусловлена наличием в течение длительного времени импортозависимости России по циркониевому сырью, осложняемой встречными потоками тотального импорта цирконового концентрата и экспорта значительной доли бадделеитового концентрата.

Цель: изучение динамики товарных потоков (производства, импорта, экспорта, потребления) циркониевого сырья в России, его цен (мировых и российских), сырьевой базы циркония России и перспектив национального производства ее добычи и переработки.

Методы: статистический, графический, логический.

Результаты: Россия импортирует подавляющее количество (98–100 %) потребляемого цирконового концентрата (3,5–14,9 тыс. т/год). Лишь в 2022 г. началось массовое национальное производство селективного цирконового концентрата при разработке Туганского титан-циркониевого месторождения, что позволит уже в 2023 г. закрыть до 30 % потребности России в циркониевом сырье, а дальнейшее строительство 2-й очереди Туганского ГОКа приведет к увеличению его предложения до 15 тыс. т/год, что полностью перекроет российские потребности в циркониевом сырье. В то же время концентрат бадделеита (природный оксид циркония), извлекаемый попутно при обогащении апатит-магнетитовых руд на Ковдорском ГОКе, до 2017 г. практически весь (96–100 %) отправлялся на экспорт (4,0–9,3 тыс. т/год) и лишь с 2018 г. наметилось снижение экспортных поставок и увеличение его национального потребления (до 60 % от производства).

В 2022 г. прекратился импорт цирконового концентрата с Украины и осложнились его поставки из недружественных стран. Для покрытия временного дефицита российского потребления цирконового концентрата (3–5 тыс. т/год) возможны поставки от независимых производителей из дружественных стран, в том числе и по схеме параллельного импорта. Снижение временного дефицита циркониевого сырья возможно также переориентированием части экспортного потока бадделеитового концентрата на российские нужды.

На территории России имеются подготовленные месторождения, включающие полезный циркониевый компонент, но для всех них имеются экономические и технологические сложности их освоения. Это Лукояновское, Бешпагирское, Туганское, Центральное и Тарское титан-циркониевые погребенные россыпные месторождения, Катугинское, Улуг-Танзегское, Зашихинское и Сахарйокское комплексные рудные цирконсодержащие редкометалльно-редкоземельные месторождения, участок эвдиальтовых руд Аллуайв на Ловозерском редкометалльном месторождении.

Кроме развития уже организованных добычных работ на Туганском титан-циркониевом месторождении, ведутся работы по подготовке Зашихинского месторождения, где при обогащении тантал-редкоземельных руд будет дополнительно извлекаться до 8 тыс. т/год цирконового концентрата.

Возможно также создание зарубежных совместных предприятий по добыче циркониевого и титанового сырья в дружественных странах (во Вьетнаме и ЮАР) для последующих поставок добытого сырья в Россию.

Наметившийся тренд снижения импортозависимости России по циркониевому сырью, а в дальнейшем и полная ее ликвидация позволят нарастить потребление циркона и оксидов циркония в самом емком направлении их использования – для глушения глазури керамической плитки. Наличие независимой и достаточной национальной добывающей базы циркониевого сырья позволит развивать российское производство циркония металлического, циркониевых огнеупорных и абразивных продуктов, твердотопливных энергетических элементов и других цирконийсодержащих приложений.

Ключевые слова

стратегическое сырье, импортозависимость, циркон, бадделеит, цирконий металлический, оксиды циркония, экспорт, национальные проекты

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Introduction

At the present time, the situation regarding the manufacture and consumption market of zirconium raw materials in Russia is challenging. The situation is burdened with high risks of failures to ensure the movement of commodity flows.

In world zirconium production, the main uses of zirconium are the production of ceramic products (54 %), non-stick coatings (14 %) and refractory products (13 %) in the foundry industry [1]. In Russia over 60 % of zirconium mineral raw materials is used in the nuclear industry for the production of metallic zirconium [1, 2]. Zirconium is included in the national list of the main types of strategic mineral raw materials (Order of the Russian Federation Government as at 16 January, 1996, №. 50-r). In the Strategy for the Development of the Mineral and Raw Material Base of Russia until 2030, it belongs to the problematic third group of scarce minerals, internal consumption of which is largely provided by enforced imports (Decree of the Government of the Russian Federation of December 22, 2018, № 2914-r).

The greatest difficulties for the Russian zirconium industry arose after the collapse of the USSR, when the main supplies of zirconium raw materials were provided from the existing mining and processing complexes (MPC) (Volnogorskiy, Irshinskiy, Streminogorskiy, Mezhdurechenskiy) located on the territory of Ukraine. In the 80 years of the XX century in the USSR, up to 40 kt of *zircon concentrate* (containing 65 % ZrO2) was mined and processed annually. Since 1991 it was imported into Russia, and by 2000 Russian consumption decreased to 9 kt/year [2].

At the same time, at the Kovdorsky mining plant in the Murmansk region, during the apatite-magnetite development of the same-named deposit, 4–9.3 kt/year of associated minerals is mined – baddeleyite concentrate (natural zirconium oxide) [2]. Most (2.4–9.3 kt/year or 40–100 %) is exported.

There is an overall zircon raw material shortage for the needs of Russian industrial production which is covered by imports. There is also a contradiction between the benefits of exporting Russian baddeleyite concentrate and the problems of domestic Russian demand for this product.

Given the risks of the consequences of anti-Russian economic sanctions by the EU and the USA, the real current state of the Russian zirconium industry needs to be determined.

Methodology

In order to study the Russian market of zirconium raw materials, data was collected on the global and Russian production of zirconium raw materials for the period 1996–2020, as well as the dynamics of Russian and world prices for zirconium products for the period 1996–2022. Sources of information were: Bulletins and survey reports of the Russian Ministry of Natural Resources and Environment[1], data of foreign trade of the Federal Customs Service of Russia[2], data of the British Geological Surveys[3] and the United States Geological Surveys[4], data of the UN Information Service and reviews[5] of marketing companies[6]. Mining, production, imports, exports and consumption are reported in metric tons. Prices for zirconium products are quoted in USD per metric ton of the specific commodity. When calculating the sum of zirconium products of different qualities, they are given in terms of 100 % ZrO_2 in metric tons.

Condition of the Russian zirconium industry

Mining. In world practice, the main source of zircon concentrate is titanium-zirconium coastal marine alluvial deposits. These are very technologically advanced in terms of mining and enrichment of ore sands. The world leaders in zircon mining are: Australia (400–620 kt/year); South Africa (320–390 kt/year); USA (70–100 kt/year); and Sene-

[1] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[2] Federal Customs Service of Russia. URL: http://stat.customs.ru/analytics/

[3] US Geological Survey. URL: National Minerals Information Center | U.S. Geological Survey (usgs.gov)

[4] Britain Geological Surveys. URL: Commodities & statistics | MineralsUK (bgs.ac.uk)

[5] UNdata. A world of information. URL: https://data.un.org/Default.aspx

[6] TrendEconomy. URL: https://trendeconomy.ru/

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gal (50–100 kt/year)[7]. In Russia, despite a sufficiently established resource base for explored titanium-zirconium sand deposits, the extraction of zircon (zirconium silicate containing 65 % ZrO_2) has not been carried out due to the presence of a stable zircon import flow (together with ilmenite and rutile) concentrate from Ukraine. In 2007–2015, the pilot operation of the Tugan titanium-zirconium deposit in the Tomsk region was carried out with an annual zircon concentrate output of 79–936 t/year [2, 3]. In 2022, the construction of the 1st stage of the Tugansky GOK of JSC Ilmenit was completed (Fig. 1). This provided production of 410 tons of zircon concentrate by the end of the year and expected output of 3.5–3.7 kt in 2023. This meets 30–35 % of Russian demand for this product. The construction of the 2-nd stage of the Tugansky GOK planned for 2025 will increase the zircon concentrate output to 14.7 kt/year. This will completely cover Russian demand for zirconium raw materials [3].

[7] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

Baddeleyite (zirconium natural oxide) is a rare industrial type of mineral raw material, periodically mined in the weathering crusts of carbonatites of the Poços de Caldas deposit in Brazil (1940–1950s). It has also been extracted during beneficiating of apatite-copper ores of the Palabora carbonatite deposit in South Africa (1964–2001). In Russia, starting from 1975, baddeleyite has been extracted during beneficiating of baddeleyite-apatite-magnetite ores of the Kovdor carbonatite deposit and the Kovdorskiy GOK of MCC EuroChem (see Fig. 1) [2, 4]. Since baddeleyite concentrate is an associated useful component, its production volumes are practically not regulated. This is due to the variability in the quality of the composition of ores (containing only 0.13–0.16 % ZrO_2), controlled to optimize the production of the main commodity component – iron ore concentrate. Accordingly, the production volumes of baddeleyite concentrate are variable over time (4.0–9.3 kt/year). They show trends of initial increase from a local minimum of 4.0 kt in 1999, to a maximum of 9.3 kt in 2010 and a subsequent downward trend in supply down to 6.0 kt in 2020 (Fig. 2).

Fig. 1. Enterprises mining, processing and consuming zirconium raw materials, Metallogenic provinces of the location of zircon-bearing placers and the actual zirconium deposits:
1 – metallogenic provinces of location of zircon-bearing placers (I – Unecha-Krapivnenskaya; II – Central Chernozem; III – Penza-Murom; IV – Lukyanovskaya; V – North Caucasus; VI – Timan; VII – Zauralye; VIII – Tara; IX – West Siberian-Khatanga); *2* – titanium-zirconium placer deposits; *3* – zircon-bearing complex rare-metal deposits; *4* – baddeleyite deposits in carbonatites; *5* – baddeleyite deposits in the weathering crusts of carbonatites; *6* – enterprises extracting zirconium raw materials; *7* – metallurgical enterprises for the production of metallic zirconium; *8* – other enterprises consuming zirconium raw materials

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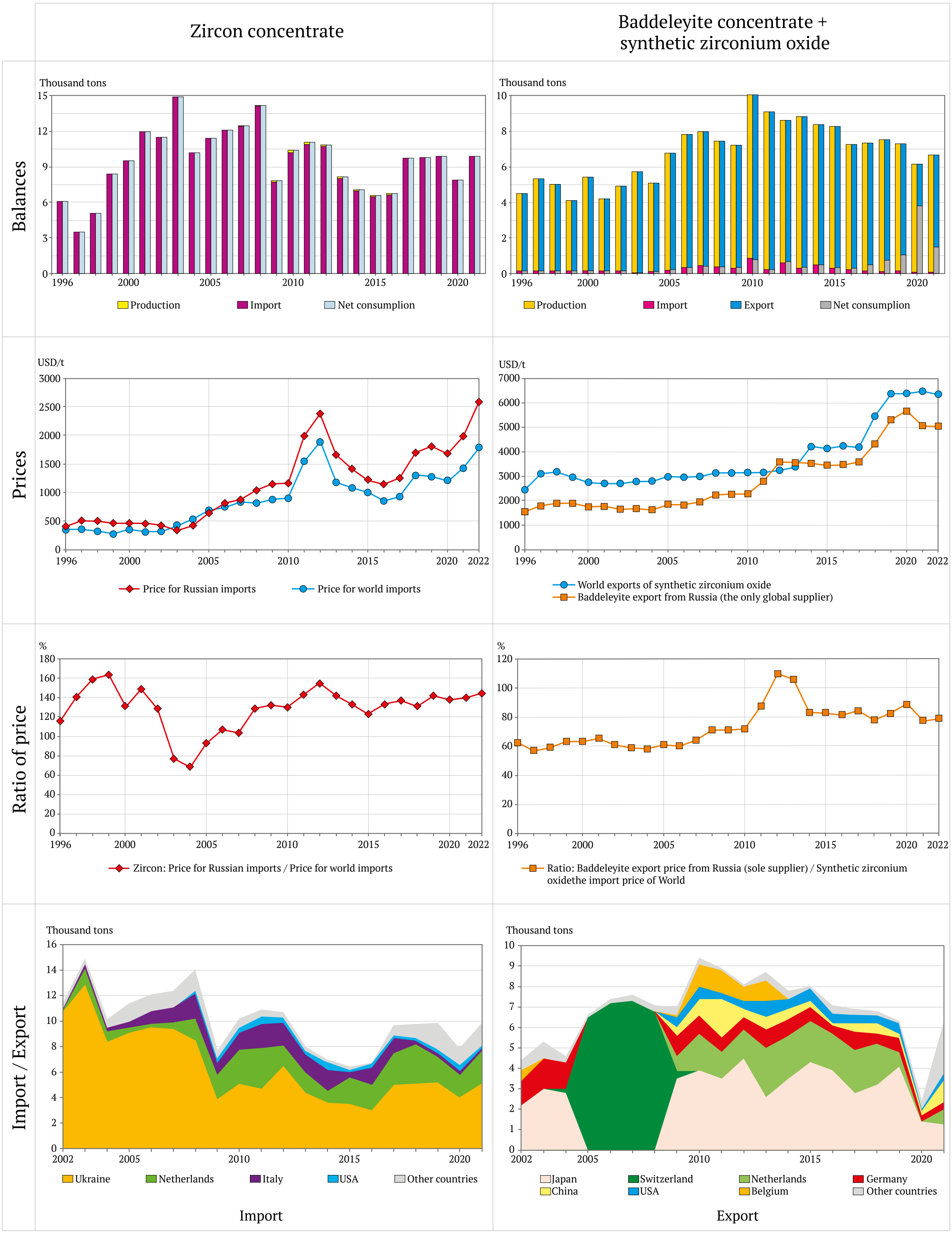

Fig. 2. Dynamics of indicators of zircon and baddeleyite concentrates commodity flows for 1996–2021(2022)

Baddeleyite makes up 99–100 % of total zircon raw materials production in Russia. The share of zircon production does not exceed 1.4 %. In relation to world production of zirconium raw materials, the share of Russian supply is 0.6–1.1 %. This figure fluctuates relative to the average level of 0.8 % (Fig. 3) – a very small contribution to the volume of world consumption of zirconium products (528–1127 kt/year in terms of 100 % ZrO_2).

Import. The vast majority of *zircon concentrate* (98–100 %) prior to 2021 inclusive was supplied to Russia by import (3.5–14.9 kt/year), see Fig. 2. The main commodity flow of zircon was from Ukraine (3.0–12.9 kt/year or 43–94 %). This was due to the traditional nature of the usual commodity flows of zircon and, in particular, its lower radioactivity when compared to zircon concentrate from South Africa and the USA [5]. However, if in the 1990s and 2000s, the overwhelming share of imports of zircon concentrate came from Ukraine (75–94 %), then in the 2010s, supplies from the Netherlands (up to 32 %), Italy (up to 24 %) and the USA increased (up to 9 %), see Fig. 2. There were small import inflows of zircon concentrate from Indonesia, China, Kazakhstan. In 2022, the import of zircon concentrates from Ukraine stopped and its supplies from unfriendly countries became more complicated.

Average world import prices for zircon concentrate in 1996–2002 were at the level of 310–360 USD/t. In 2003, their growth began against the background of increased consumption in China (20 % of world demand in 2002 and 60 % in 2012) up to 1534 USD/t in 2012. The global economic crisis of 2008–2009 years affected the growth of zircon price trend only by slowing down its increase (see Fig. 2). Subsequently, against the background of a decrease in the volume of consumption of zircon concentrate in China, its average world prices decreased to 860 USD/t in 2016. Later, with a resumption in demand, their growth resumed up to 1780 USD/t in 2020.

The price of imported zircon concentrate only in 2003–2005 (during the initial period of growth in its consumption in China) was lower than the average world export prices by –24 ...–32 % (see Fig. 2). There was an excess of the price of Russian imports over world prices by +20...+60 % over the years. This can be explained by the declared higher quality of Ukrainian zircon concentrate [5]. In general, against the backdrop of the general global price increase, the cost of Russian imports of zircon concentrate increased from USD 2.6 million in 1996 to USD 25.4 million in 2012. Subsequently, against the backdrop of a decline in import volumes, this amounted to USD 8–18 million, USD/year.

There are also small volumes of imported synthetic *zirconium oxide* (analogous to natural baddeleyite) – 51–852 t/year (see Fig. 2), mainly of high-quality varieties. 96–172 tons/year of *metallic zirconium* are also imported.

Export. Prior to 2017, almost all of the *baddeleyite concentrate* produced at Kovdorsky mining and processing complex was exported (96–100 %), see Fig. 2. This was facilitated by a high level of world prices and limited volumes of world trade in natural and synthetic *zirconium oxide*. The dynamics of export supplies of baddeleyite concentrate almost completely mirror the trends in the production of baddeleyite. There was an initial increase from a local minimum

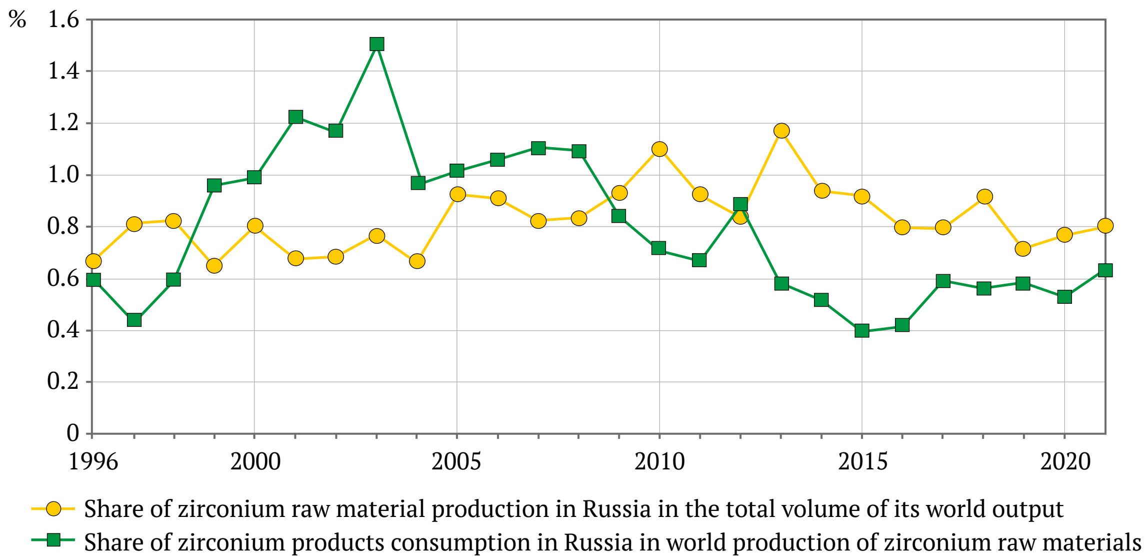

Fig. 3. Shares of the Russian production and consumption of zirconium raw materials in terms of its global output for 1996–2021 (in recalculation on 100 % ZrO_2)

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of 4.0 kt in 1999 to a maximum of 9.3 kt in 2010 to a subsequent trend of decreasing exports up to 6, 9 kt in 2017, and then their sharp reduction to 2.6 kt in 2020 (40 % of production), see Fig. 2. The main buyers of Russian baddeleyite concentrate were: Japan (up to 65 % of Russian supply); the Netherlands (up to 30 %); and Germany (up to 28 %), see Fig. 2. In 2005–2008 the export flow of baddeleyite concentrate from Russia passed through intermediary companies in Switzerland, see Fig. 2.

In general, the market for zirconium oxide international trade (natural + artificial) is relatively small – (29–52 kt/year). It corresponds to 3.9–6.3 % of the world production / consumption of zirconium raw materials (in terms of on ZrO_2), see Fig. 4. The share of Russian exports of baddeleyite (4.8–9.3 kt) in the world trade of zirconium oxides is 12–22 % (see Fig. 4).

For a long period (1996–2013), world trade prices for synthetic zirconium oxide remained approximately at the same level of 2700–3350 USD/t. Subsequently, there have been jumps in price growth with a subsequent stability of their level of 4200–4300 USD/t in 2014–2017 and 6400–6500 USD/t in 2019–2022 (see Fig. 2). The 2008–2009 global economic crisis did not affect the dynamics of prices for zirconium oxides. The price rises for zirconium oxide in 2013 and 2018 fell at the moments of decrease in the volumes of Russian production and, accordingly, export of baddeleyite concentrate.

The export price of Russian baddeleyite concentrate in 2002–2010 was below the average world import prices of synthetic zirconium oxide by −28, ...−48 % with a downward trend over time (see Fig. 2). Between 2012–2013, there was only one period when the prices of Russian exports exceeded average world prices by 6–10 %. This was due to a larger share of the output of ceramic varieties of baddeleyite produced at that time. Between 2014–2022, Russian baddeleyite concentrate was again sold at a discount of +10...+22 %. The value of the Russian baddeleyite concentrate export increased from USD 6.8 million in 1996 to a maximum of USD 33.5 million in 2019. However, it dipped sharply with the fall of export volumes to USD 13.7 million in 2020.

Consumption. The main consumer of imported and domestic *zircon concentrate* in Russia is SC Chepetsky Mechanical Plant (ChMP) in Glazov (Republic of Udmurtia). It produces metallic zirconium and products for the needs of the nuclear industry, as well as synthetic zirconium dioxide. ChMP in the 2010s produced up to 3000 tons of metal zirconium [2] annually, obtained by processing up to 5000 tons of zircon concentrate[8] [5].

LLC Kerama Marazzi at the Orlovsky plant of ceramic tiles, produces zircon concentrate to muffle the enamel of ceramic tiles. Consumption is 0.8–1.3 kt/year[9].

JSC Klyuchevskoy Ferroalloy Plant (settlement Dvurechensk, Sverdlovsk region), annually produces up to 150 tons of ferrosilicon zirconium for deoxidi-

[8] Federal Customs Service of Russia. URL: http://stat.customs.ru/analytics/

[9] I bid.

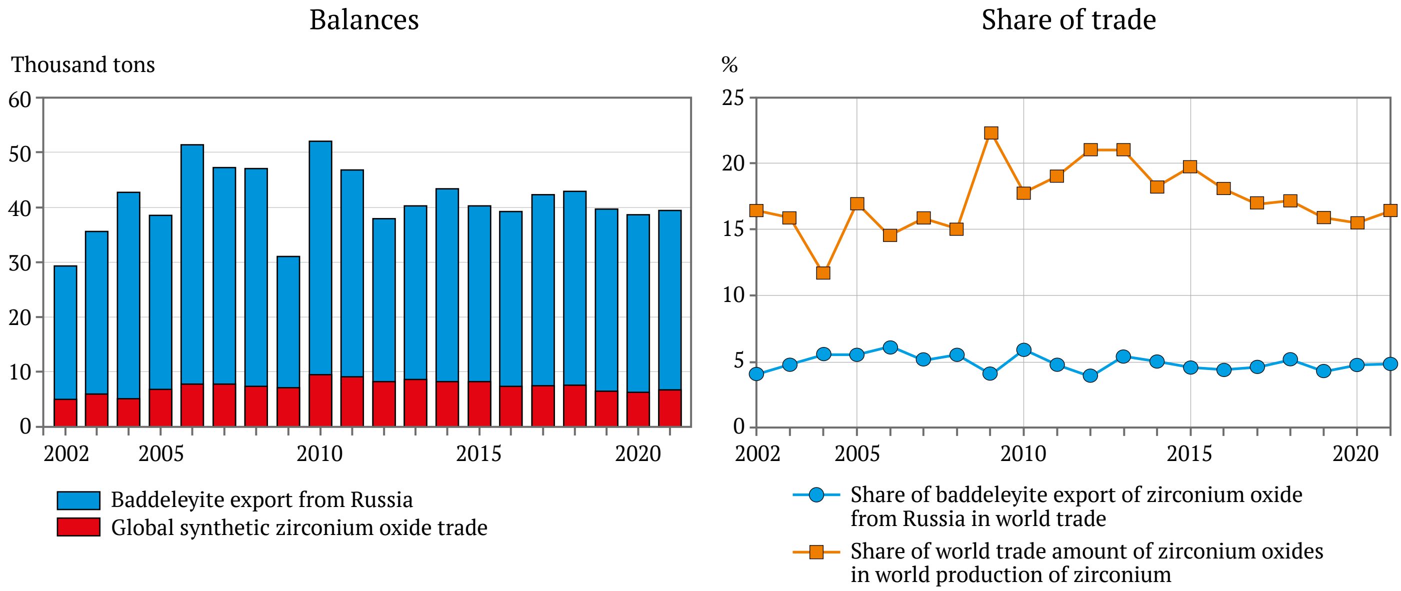

Fig. 4. Dynamics of world trade balances of natural and synthetic zirconium oxides, as well as the share of baddeleyite export from Russia of the total zirconium oxide world trade and the share of zirconium oxide world trade in the world production of zirconium raw materials for 2002–2021 (in terms of 100 % ZrO_2)

zing steel and increasing its strength. Consumption is up to 250 tons of zircon concentrate [6].

Zircon concentrate is also used for the manufacture of anti-burning paint for coating crucibles and molds directly at ferrous and non-ferrous metallurgy enterprises [7]. However, there are no statistics on the volume of this use.

A significant part of imported zircon concentrate (3–5 kt/year) is processed into zirconium dioxide for use in the production of refractory materials and ceramics.

The processing of zircon concentrate for zirconium dioxide (including doping with calcium or yttrium) is carried out at Russian enterprises: ORPE Technologiya named after A.G. Romashin and LLC Technokeramika (Obninsk, in the Kaluga region), JSC DINUR (Pervouralsk, Sverdlovsk region).

LLC Technokeramika, in addition to zirconium oxides, produces abrasive materials from zirconium oxides (Zirco+).

ORPE Technologiya named after A.G. Romashin produces refractory materials based on zirconium oxides: zirconium dioxide ceramic film; porous elements and diaphragms for electrochemical water purification; layered structures with zirconium dioxide coatings for insulating or sealing elements for electrochemical devices; nozzles and bushings for metal melt spraying installations; solid electrolytes of electrochemical solid oxide fuel cells and oxygen pumps; oxygen concentration sensors in metal melts; crucibles for ferrous and non-ferrous metallurgy for heat treatment of various materials; electrochemical elements in dynamic oxygen sensors of on-board security and life support systems; and in nuclear power engineering.

STC Bakor (Moscow), EFR Sherbinka (Shcherbinka, the Moscow region) and JSC Borovichi Refractories Plant (BRP) in Borovichi (the Novgorod region) produce corundum oxide zirconium refractory products and mortars (bulk refractories) for the glass industry. They also produce products for continuous casting of steel based on zirconium dioxide, or with the addition of zircon.

According to the dynamics of Russian consumption of zircon concentrate, there has been a significant increase in consumption from 3.5 kt in 1997 to 15 kt in 2004. There was stabilization at the level of 10–12 kt/year until 2012 with a crisis drawdown of up to 7.7 kt in 2009, after which the consumption of this marketable product has fluctuated in the range of 8–11 kt/year (see Fig. 2). In terms of 100 % ZrO_2, the minimum annual consumption of zircon was 3.2 kt in 1997, the maximum was 9.7 kt in 2003, and the most recent in 2020 was 6.4 kt (see Fig. 1).

In terms of the dynamics of the Russian primary supply of zirconium oxides (baddeleyite + imports of synthetic zirconium oxide), there has been an increase in consumption from 0.15 kt in 1996 to 3.8 kt in 2020 (see Fig. 2).

In terms of the processing of imported zircon into oxides at Russian enterprises, another 2–3.5 kt are sent for sale. Thus, if by 2010 the total consumption of zirconium oxides in Russia by 2010 was up to 1 kt [8], then in 2020 it was 7.3 kt/year.

In general, in terms of domestic and imported zirconium raw materials, 30–60 % of consumed raw materials are used for the production of metallic zirconium. 40–60 % are used for refractory products, up to 20 % for ceramics, up to 5 % for abrasive materials, and for ferroalloys. up to 2 %.

In world practice, more than 50 % is used in the production of mass-produced ceramic products for silencing enamel, in order to increase its strength and reducing thermal conductivity [9]. This use is constrained in Russian conditions by the total import dependence on zirconium raw materials [10]. However, the experience of creating a large-scale production of ceramic tiles at the Orel plant of LLC Kerama Marazzi. This has led to an explosive growth in the volume of its production and consumption in Russia in 2013–2015, testifying to the urgent demand for these products and, accordingly, the increase in demand for zircon and baddeleyite raw products.

The total import dependence of Russia on zirconium raw materials also constrains other areas of zirconium product use:

– production of powders of zirconium carbide [11] and zirconium diboride [12] for the manufacture of abrasive materials, wear-resistant coatings and as part of hard alloys;

– use of zirconium oxides (doped with yttrium or scandium) as solid electrolytes, stable at high temperatures in solid fuel cells for converting the chemical energy of hydrocarbon fuel into electricity and heat [13];

– hydrochemical production of magnesium-stabilized zirconium oxide powders for the manufacture of heat-resistant composite ceramic material [14].

Mineral raw material base. Globally, only one type of zirconium deposits is currently being developed: modern coastal-marine titanium-zirconium placers with minimal overburden volumes. *Titanium-zirconium placers* are also known on the territory of Russia. However, almost all of them are buried and with epigenetic changes in the properties of useful minerals [15]. This complicates their development and reduces investment attractiveness. The most attractive of them in terms of quality and quantity of zirconium raw materials are[10] [2]:

– Lukoyanovskoye deposit in the Nizhny Novgorod region, containing an average of 13 kg/м^3 of zircon in sands, reserves of 389 kt of ZrO_2;

– Beshpagir deposit in the Stavropol Territory, 7.84 kg/м^3, 166 kt;

– Tugan deposit in the Tomsk region, 7.65 kg/м^3, 1007 kt;

– Central deposit in the Tambov region, 6.7 kg/м^3, 830 kt;

– Tarskoye deposit in the Omsk region, 6.37 kg/м^3, 181 kt.

At present, the construction of the 1st stage of the Tugansky GOK of JSC Ilmenit has been completed. The commercial operation of the Tugan titanium-zirconium deposit has begun with an annual output of up to 3.7 kt of zircon concentrate, 11.4 kt of ilmenite concentrate, 0, 8 kt of rutile concentrate and up to 220 thousand m^3 of construction sand [3]. The Lukoyanovskoye, Beshpagirskoye and Tsentralnoye deposits are currently in unallocated subsoil.

There are also possible development projects of titanium-zirconium placer deposits in friendly countries: Vietnam (deposits Cam-Hoa, Qui-Ninh, Ke-Sung, etc.) [16], and in South Africa, where there is experience in creating Russian-African mining enterprises (importing manganese ores to Russia) [17].

Baddeleyite ores in carbonatite deposits, the only deposit is being developed in Russia – Kovdorskoye in the Murmansk region[11], including significant reserves of zirconium (2182 kt ZrO_2). They are also developed as an associated component of complex apatite-magnetite ores (average content of 0.15 % ZrO_2) [2]. Moreover, due to the status of associated raw materials for baddeleyite, there are low rates of extraction into concentrate (30–40 %) and the formation of tailings rich in this mineral. At Kovdorsky GOK, a technogenic deposit has now been formed, including 34 kt of ZrO_2. Technology needs to be developed for the enrichment of baddeleyite-containing ores with an increase in its extraction into concentrate.

A pure baddeleyite deposit is also known in Russia: Algama in the Khabarovsk region. This is a genetic analogue (carbonatite weathering crust) of the Posos de Caldas deposit in Brazil [18]. However, the Algaminskoye deposit is located in a remote area outside transport communications, has not been explored. It is unlikely to be of industrial interest in the near future.

Other types of *complex ore deposits have previously been explored, including significant mineralization of zircon* in Russia[12]. Among the most notable of these are:

– Katugin zircon-pyrochlore-cryolite deposit in the Trans-Baikal region, with reserves of 3086 kt of ZrO_2 with an average content of 1.6 % ZrO_2;

– Ulug-Tanzek zircon-pyrochlore-columbite deposit in the Republic of Tyva, 2900 kt, 0.4 % ZrO_2;

– Zashikhinsky zircon-pyrochlore-columbite deposit in the Irkutsk region, 282 kt, 0.46 % ZrO_2;

– Sakharjok deposit in the Murmansk region with resources of 1625 kt of ZrO_2.

Complex deposits can be challenging in terms of enrichment of their ores, selectivity in the extraction of useful minerals and components. A particular risk is managing the individual commercial product output, especially in the context of increasing prices. The main commercial product which is the focus of the main technological enrichment process with its optimal yield in terms of quality and quantity is singled out. This is also the case for all other mineral products which are accounted for upon their release as associated components. In the Katuginsky and Ulug-Tanzegsky deposits, niobium is the main attractive component of complex ores, for the Zashikhinsky – tantalum. Thus, the zirconium product for these objects is a minor associated mineral.

Currently, the Zashikhinskoye deposit (the owner of the license for subsoil use is JSC Technoinvest Alliance)[13] is at the stage of development and design of the mining enterprise. Moreover, the main attractive component of the complex ores of this project is tantalum (average grade in ores is 0.03 % Ta_2O_5). It is planned to produce annually 8.2 kt of zircon concentrate and 6 kt of pyrochlore concentrate containing 220 tons of Ta_2O_5 and 2.5 kt of Nb_2O_5 [19]. The Katuginskoye and Ulug-Tanzegskoye deposits are located in remote areas and, due to the low investment attractiveness and the difficulty of ore enriching, are in unallocated subsoil.

Outside the Russian Federation, zircon-containing complex ore deposits have also become the objects of investment attractiveness. This is especially the case against the background of the depletion of most developed titanium-zirconium placers. However, the same problem exists in terms of

[10] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[11] I bid.

[12] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[13] I bid.

the multiplicity of marketable product output, and linking production planning to the main mineral or marketable product. Projects for field development are being prepared for implementation, including the extraction of zircon concentrate: Thor Lake [20] and Strange Lake [21] in Canada, Bear Lodge in the USA [22], as well as Zandkopsdrift in South Africa [23] and Tunbreeze in Greenland [24] with the main components in the form of rare earth metals.

Eudialyte ores, an unconventional type of zirconium raw material known at the Alluive site of the developed Lovozero rare metal deposit, are also becoming attractive. The resources of zirconium in eudialyte ores at this deposit are 7275 kt of ZrO_2 with a cut-off grade of 2.5 % ZrO_2. The main component extracted from the eudialyte concentrate here is zirconium, and rare earth materials – associated useful components [25]. A positive aspect of the Alluive site development of eudialyte ores is the presence of an existing mining complex near the infrastructure. The risk factors are the absence of an enterprise for processing eudialyte concentrate and the likelihood of declaring specially protected geological natural monuments on the territory of the mining allotment of the deposit (pegmatite bodies "Shkatulka" and "Yubileinaya"). This followe the example of the Pilanesberg eudialyte deposit in the national park of the same name in South Africa.

Eudialyte ore deposits are being prepared for development abroad: the Durbo project at the Tungi deposit in Australia (the main component is zirconium) [26]; the Nechalacho project in Canada [27]; and the Kwan Fjeld project in Greenland [28] (the main components are rare earths).

Discussion and Conclusions

Since 1992 in Russia, the zirconium market has had a completely import-dependent zircon concentrate flow and a predominantly export-oriented baddeleyite concentrate flow. Only in 2022, did mass national production of selectively extracted zircon concentrate begin during the development of the Tugan titanium-zirconium deposit.

In the list of recent political sanctions, there is no reference to a trading ban with Russia for zirconium ores and concentrates. However, supplies from Ukraine have stopped, and the main world producers of zirconium raw materials are either unfriendly (USA, Australia) or controlled by the latter (operators Namacwa Sands and KZN Sands in South Africa by the American company Tronox, QMM in Madagascar by the Australian Rio Tinto, Tizir in Senegal by the French Eramet and the Australian MDL, Moma Titanium Minerals in Mozambique by the Irish Kenmare). Nevertheless, in order to cover the temporary shortage of Russian consumption of zircon concentrate (3–5 kt/year), supplies from independent producers from friendly countries are possible. Volumes of deliveries of zircon concentrate from Indonesia need to be increased, and new flows of its import from Vietnam, Sri Lanka, India, Brazil, Namibia, Kenya, Tanzania and other countries, including need to be coordinated through parallel import schemes.

It is also possible to cover the temporary zirconium raw material shortage for Russian needs by reorienting the baddeleyite concentrate commercial flow produced by Kovdorsky GOK. The needs of metallic zirconium production, for example, are 2.2–3.3 kt/year instead of 3.3–5 000 t/year of zircon concentrate [5]. The Chepetsk Metallurgical Plant has already started using baddeleyite concentrate since 2022.

When considering new projects for the zirconium raw material production, there are three groups of proposed development objects: 1) traditional placer of titanium-zirconium deposits; 2) complex ore rare-metal deposits, including the extractable useful mineral – zircon, 3) complex rare-metal deposits of eudialyte, the processing of which extracts the main useful component – zirconium.

As already noted, the development of complex deposits is planned. This is based on the release of the main useful component, and the fact that volumes of production of associated zircon concentrate have become uncontrollable. Nevertheless, the ongoing project for the development of the Zashikhinsky deposit with tantalum as the main component is feasible due to the extreme shortage (complete import dependence) of this product, Thus an additional 8 kt/year of zircon concentrate will be supplied for sale. As for the eudialytic Lovozerskoye deposit (Alluaive site), despite the high content of zirconium (the main component), the issue of development remains open. Currently there are no examples of industrial processing of such ores, but only projects and intentions to develop such deposits.

The most promising direction for the development of the national production of zirconium raw materials is the development of prepared titanium-zirconium alluvial deposits. The commissioning of the 1st stage of the Tuganskiy GOK will allow from 2023, up to 3.5 kt of zircon concentrate to be produced (30 % of the Russian demand for this product). The further construction of the 2nd stage of mining and processing complex will lead to an increase in its supply to 15 kt/year, This will completely cover the Russian demand for zirconium raw materials. Due to the increase in Russian demand for zirconium raw materials, projects may be implemented to develop the Central, Lukyanovskoye, Beshpagirskoye and Tara alluvial titanium-zirconium deposits. However, at the same time, the main components of their output will be ilmenite and rutile concentrates with a subordinate value of associated zircon concentrate. The main problem in the development of Russian placer titanium-zirconium deposits is the difficulty in ensuring the satisfactory quality of the resulting commercial concentrates. One of the reasons for the low quality of concentrates is the presence of newly formed films of limonite, kaolin and other exogenous minerals on zircon, ilmenite and rutile grains. This problem needs to be solved through the development and application of new technologies for the enrichment of concentrates, which will increase the economic efficiency of the development of Russian alluvial deposits.

The creation of foreign joint ventures for the extraction of zirconium and titanium raw materials in Vietnam and South Africa for subsequent supplies of the extracted raw materials to Russia is possible. However, the influence of the time factor arises in coordination with the commissioning of new national production of zirconium and titanium raw materials. Nevertheless, the issue remains relevant, and the implementation of these projects should be aimed not only at Russian demand for this raw material, but also at world markets.

The emerging trend of reducing import dependence on zirconium raw materials, and in the future its elimination will allow the consumption of zircon and zirconium oxides to be increased in the most capacious direction of their use: dampening the glaze of ceramic tiles. The presence of an independent and sufficient national mining base of zirconium raw materials will allow the development of the Russian production of metal zirconium, zirconium refractory and abrasive products, solid fuel energy cells and other zirconium-containing applications.

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