Investigation of the technology for extracting vanadium semi-products from Sijjak ore fields

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Abstract. The paper provides an in-depth analysis of the possibilities for extracting vanadium metal from the ores of the Sijjak deposit, the composition of minerals, and their enrichment technologies. During the research, the physicochemical properties of the ores were studied. It was determined that the main elements in their composition are vanadium, iron, aluminum, silicon, and other compounds. The initial raw material composition was determined using X-ray phase analysis, SEM, SEM-EDX, and atomic emission spectroscopy methods. The composition and purity of the purified vanadium pentoxide obtained through enrichment, selective leaching, and processing were investigated using the aforementioned methods. To extract vanadium in its oxide form, a calcination technology with the addition of sodium carbonate at a temperature of 700°C and a method for producing sodium vanadate compounds have been developed. The experiments made it possible to increase the degree of vanadium transfer to the total solution up to 92.8%. Based on the research results, a combined pyrometallurgical and hydrometallurgical technological scheme for extracting vanadium from the Sijjak deposit ores was proposed, and optimal parameters were developed. A material balance of the created technological scheme has been developed, and a chain of recommended technological equipment for industrial application has been proposed.

1 Introduction

Vanadium is a metal widely used in steel production, described by scientists as a vitamin, and it possesses the property of "calming steel." Adding vanadium to cast iron increases its tensile strength and hardness resistance. Currently, vanadium production worldwide is mainly carried out by several major producing countries. Leading manufacturers include China (Chengde Iron & Steel Group Co Ltd and Panzhihua Group), Russia (Vanadium-Tula), and South Africa (Xstrata and Highveld Steel & Vanadium Co Ltd), which account for more than 90% of global production. China is particularly the largest producer, with vanadium mainly extracted from waste products of iron ore enrichment and the steel industry [1].

Globally, vanadium is primarily produced in the form of vanadium pentoxide (V_2O_5), which is subsequently used to obtain metallic vanadium, ferrovanadium, or vanadium chemical compounds. In recent years, the development of green energy technologies

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(especially vanadium redox flow batteries) has significantly increased the demand for this metal. With the growing global demand for vanadium, interest in developing new deposits, improving processing technologies, and utilizing renewable sources is increasing. This may affect the geoeconomic balance of this strategic resource in the future. The processes of extracting vanadium pentoxide from the Sijjak ore fields in Uzbekistan are being studied by researchers for the first time, and the findings are of a recommendatory nature for industrial enterprises, based on the results of scientific research [2].

The analysis of literature revealed that the studied technologies are ineffective for the ores of the Sijjak deposit. Consequently, additional research is required on the processes and technologies for extracting vanadium from vanadium-containing raw materials in the form of pentoxide and ferroalloys. This work is specifically dedicated to developing a technology for processing vanadium from the ores of the Sijjak deposit using a combination of pyrometallurgical and hydrometallurgical technologies.

2 Materials and methods

Samples were collected to study the material and mineralogical composition of the Sijjak deposit. These samples underwent preparatory processes such as crushing, grinding, and homogenization to determine the average content of the valuable metal. Studies revealed that important vanadium minerals occur alongside patronite (vanadium sulfide), pure sulfur, carbonaceous matter, silica (sandy soil), and calcite. During calcination, this mineral loses up to 45% of its weight, after which the vanadium content reaches 52%. Patronite ores are easily calcined, therefore roasting can be widely used for ore beneficiation. After roasting, the calcine contains sulfate sulfur and non-combustible compounds such as iron, silicon, nickel, titanium, and aluminum oxides. It was established that V_2O_5 transitions from the oxide form to the vanadate form.

The main ore-forming minerals of the Sijjak deposit are wulfenite, vanadinite, and descloizite, which have been repeatedly identified by mineralogists and geologists in this deposit. According to geological studies, wulfenite and its accompanying minerals are formed by the contact of an uneven layer filled with iron hydroxides and brown clays with a steep tectonic fault zone. One of the characteristic minerals of the Sijjak deposit is vanadinite ore. Vanadinite is the primary metal-carrying compound of vanadium and is considered a vanadium oxide mineral. A comprehensive chemical analysis was conducted on samples taken from various points of the Sijjak deposit. The results of the chemical analyses are presented in Table 1. Initially, an X-ray phase analysis of the ores was carried out. Diffractograms of powder samples were studied using the semi-quantitative X-ray phase analysis method [3].

The results of semi-quantitative spectral analysis (Table 1) show that the vanadium content ranges from 0.003% to 0.007%. This is significant considering that the current technological minimum for profitable extraction of this metal is 0.001% or 100 g/t in terms of production value. In our case, the vanadium content in the initial ores of the Sijjak deposit reached 300-700 g/t. Furthermore, SEM and SEM-EDX analyses revealed contents of up to 1500 g/t, with numerous tested samples showing vanadium concentrations ranging from 2500 to 6500 g/t (0.25-0.65%). Given that the Sijjak deposit is a newly discovered ore body, extensive research was conducted on the ore samples. The spectral analysis results presented in Table 1 indicate a vanadium content of 400 g/t. Additionally, high quantities of several associated metals were detected, and the average content of these supplementary metals generates significant interest for industrial-scale ore processing.

Table 1. Results of semi-quantitative spectral analysis of Sijjak deposit ores.

No	Sample No	Si	Al	Ca	Na	K	Fe	Mg	P	Ba	Sr	B	Mn	V	Ti
		Mass percentage %													
1	No1	0.3	0.02	>32	0.01	-	0.05	0.5	-	-	0.03	0.02	0.007	0.07	0.004
2	No2	0.4	0.04	>35	0.01	-	0.04	0.4	-	-	0.02	0.02	0.009	0.05	0.006
3	No3	0.5	0.02	>31	0.01	-	0.03	0.3	-	-	0.03	0.01	0.008	0.08	0.008
4	No4	0.4	0.02	>30	0.01	-	0.04	3	-	-	0.02	0.01	0.006	0.06	0.008
No	Sample No	**Cr**	**Pt**	**Pd**	**Os**	**Ir**	**Au**	**Ag**	**Cu**	**Pb**	**Zn**	**As**	**Bi**	**Ni**	**Co**
		Mass percentage %													
1	No1	-	-	-	-	-	-	-	0.008	0.009	-	-	-	-	0.03
2	No2	-	-	-	-	-	-	-	0.006	0.008	-	-	-	-	0.03
3	No3	-	-	-	-	-	-	-	0.004	0.007	-	-	-	-	0.02
4	No4	-	-	-	-	-	-	-	0.007	0.006	-	-	-	-	0.01

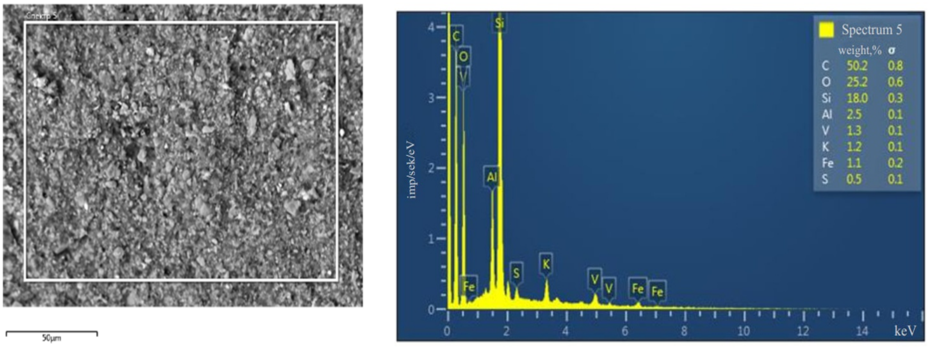


Fig. 1. Spectrogram of spectrum 5 in the ore sample from Sijjak mine.

The core of the research involves studying methods for extracting vanadium from ore raw materials in the form of pentoxide and vanadium-containing products through calcination, followed by aqueous leaching, selective acid leaching, various precipitation techniques, and calcination processes. Based on this approach, the work extensively utilized modern physico-mechanical, chemical, and physico-chemical research methods, including IR spectroscopy, atomic emission analysis, granulometric analysis, and electron microscopy.

Spectral analysis data indicate the presence of low amounts of natural carbon and sulfur, which characterizes the ore as having a low-sulfide oxide formation. As shown in Figure 1, the mineralized particles of vanadium-containing ores appear as finely dispersed particles ranging from 5 to 100 μm in size. This explains the ineffectiveness of the gravitational method in ore beneficiation, as vanadium is present in oxide form in the ores, which also limits the applicability of flotation beneficiation schemes. Vanadium-containing solutions were examined using atomic emission spectroscopy, while SEM-EDX was employed to determine particle sizes in the initial ores and to analyze the composition and quantity of precipitates formed during vanadium precipitation from acidic solutions. In the studied samples from the Sijjak deposit, a spectrogram revealed an increased vanadium content of up to 1.3%, with preliminary results presented in Figure 1.

The spectrogram table 5 of the studied sample 11 shows a mixture of minerals, depicting oxide compounds of iron and aluminum, as well as some iron sulfide minerals. Additionally, the simultaneous increase of vanadium peaks with oxygen indicates the presence of its pentavalent and trivalent oxides. The occurrence of 18% silicon in the form of oxygen compounds suggests ore mineralization in the form of quartz, alumina, magnetite, and carbon compounds. The results of the elemental analysis of the studied sample 11 are presented in Table 2 below.

Table 2. Results of spectral analysis of Sijjak mine ores.

No	**Lab No**	**Geol No**	**Li**	**Be**	**B ***	**Na ***	**Mg ***	**Al ***	**P ***	**K ***	**Ca ***	**Sc**
	Measurement range	**Mineral**	**0.05-4000**	**0.05-4000**	**0.10-4000**	**0.004-11%**	**0.004-11%**	**0.002-20%**		**0.008-30%**	**0.005-28%**	**0.10-4000**
1	1-1	Mineral content, g/t	18.0	1.90	22.0	710	1300	8200	1100	6800	2700	7.80
No	Lab No	Geol No	Ti *	V	Cr	Mn	Fe *	Co	Ni	Cu	Zn	Ga
	Measurement range	Mineral	0.0006-9%	0.10-4000	1.0-4000	0.002-10%	0.006-30%	0.10-4000	1.0-4000	1.0-4000	1.0-4000	0.10-4000
1	1-1	Mineral content, g/t	1200	400	86,0	33,0	7400	1,10	10,0	**570**	26,0	25,0
No	Lab No	Geol No	As	Se	Rb	Sr	Y	Zr *	Nb	Mo	Ag	Cd
	Measurement range	Mineral	0.10-4000	0.50-4000	0.10-4000	0.10-4000	0.10-4000		0.005-4000	0.10-4000	0.05-10,0	0.005-4000
1	1-1	Mineral content, g/t	15.0	8.40	25.0	300	23.0	36.0	3.90	170	**1.80**	0.120
No	Lab No	Geol No	In*	Sn	Sb	Te	Cs	Ba	La	Ce	Pr	Nd
	Measurement range	Mineral		0.10-10	0.10-4000	0.30-4000	0.02-4000	0.10-4000	0.50-4000	0.04-4000	0.01-4000	0.01-4000
1	1-1	Mineral content, g/t	<0.05	1.30	10.0	<0.3	1.90	3700	19.0	15.0	3.50	17.0
No	Lab No	Geol No	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	Measurement range	Mineral	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000	0.01-4000
1	1-1	Mineral content, g/t	3.50	5.00	3.00	0.42	3.80	0.540	1.80	0.34	2.70	0.500
No	Lab No	Geol No	Ta	W	Re	Pt*	Au *	Tl	Pb	Bi	Th	U
	Mineral	0.05-4000	0.04-4000	0.08-4000	0.01-4000	0.05-4000	0.05-4000	0.01-4000	0.1-4000	0.01-4000	0.01-4000	0.01-4000
1	Mineral content, g/t	1.30	0.360	2.20	0.057	<0.05	<0.05	1.00	28.0	0.17	2.40	79.0

Several spectra were studied in a single area of the sample, which yielded different results. Interestingly, among the samples examined, it was specifically in sample 12 that 7 spectra of the oxidized mineral were observed (Figure 2), where a high content of vanadium could be seen.

The vanadium content in the studied sample reaches up to 2.5%, indicating that an extremely rich vanadium portion of the sample was examined, with the average vanadium content in this particular sample being 25,000 g/t. This explains why vanadium oxide mineral was captured under the microscope objective in the studied surface area of sample 12. However, this does not allow for a conclusion about such high enrichment of the entire ore.

Table 3. Results of the elemental composition of spectrum 5 from sample 11 of the Sijjak deposit ore.

Element	Relative concentration	k ratio	Weight, %	Sigma Weight, %	Standard Designation
C	1.31	0.01312	50.18	0.79	C Vit
O	1.73	0.00581	25.20	0.56	SiO_2
Al	0.26	0.00189	2.49	0.09	Al_2O_3
Si	1.87	0.01478	17.98	0.32	SiO_2
S	0.05	0.00039	0.49	0.06	FeS_2
K	0.12	0.00104	1.24	0.08	KBr
V	0.10	0.00103	1.33	0.13	V
Fe	0.08	0.00085	1.09	0.16	Fe
Total:			100.00		

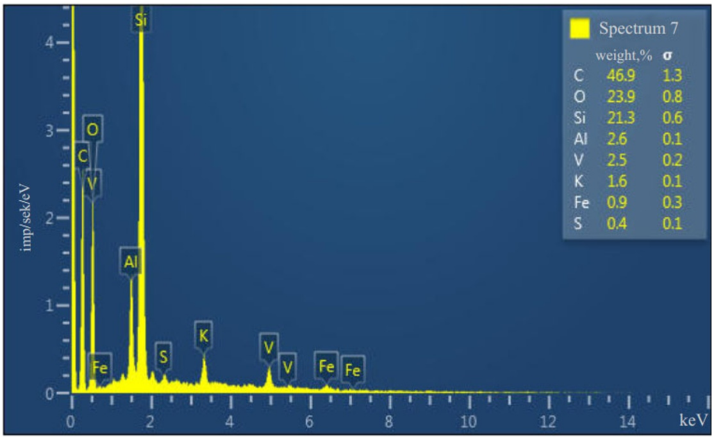


Fig. 2. Spectrogram image of spectrum 7 from sample 11 of Sijjak ore deposit.

Table 4. Elemental composition in the 7th spectrum of sample 12 from the Sijjak ore deposit.

Element	Relative concentration	k ratio	Weight, %	Sigma Weight, %	Standard Designation
C	0.85	0.00850	46.88	1.25	C Vit
O	1.24	0.00419	23.94	0.82	SiO_2
Al	0.21	0.00152	2.57	0.14	Al_2O_3
Si	1.72	0.01360	21.27	0.55	SiO_2
S	0.02	0.00021	0.35	0.09	FeS_2
K	0.12	0.00102	1.57	0.14	KBr
V	0.15	0.00149	2.48	0.24	V
Fe	0.06	0.00057	0.94	0.28	Fe
Total:			100.00		

The presence of 21.3% silicon content and oxygen compounds indicates the presence of quartz, alumina, and small amounts of iron oxide compounds in the ore. Table 4 below illustrates the presence of oxidized vanadium minerals in the studied sample No. 12 in amounts of up to 2.5%, and the results of elemental analysis are presented in spectrum No. 7. Figure 2 of spectrogram No. 7 shows the highest concentration of vanadium in the Sijjak ore field, which demonstrates vanadium mineralized in the form of vanadium pentoxide and approaching the highest content in combination with oxygen.

3 Results and discussion

The study focused on developing a roasting technology using sodium-containing binders to convert vanadium from low-grade ores into water-soluble sodium vanadate through preliminary roasting. Optimal process parameters were developed [4]. Experimental tests revealed that a two-stage leaching scheme of the obtained sodium vanadate allows for high vanadium extraction. Initially, it was found that the dissolution rate of sodium vanadate in aqueous leaching is low, but a pure vanadium solution can be obtained due to the insolubility of additional compounds. In the second stage, a technological scheme was developed for obtaining a semi-finished product from Sijjak deposit ores using combined pyrometallurgical and hydrometallurgical technologies. This scheme allows increasing the total dissolution rate to 95% through additional complete leaching of vanadium in sulfuric acid. Technological parameters were established, and the material balance of vanadium movement in technological processes was calculated.

The roasting process was carried out at different temperatures. At 600-650°C, it was observed that the roasting process did not fully occur. Conversely, at high temperatures of 800-850°C, the calcine particles adhered to each other, resulting in a low vanadium extraction rate. The roasting process proceeds according to the following chemical reaction [5]:

$$Na_2CO_3 = Na_2O + CO_2;\ \ Na_2O + V_2O_5 = 2NaVO_3$$

Therefore, 700°C was determined to be the most optimal temperature for roasting. The results are presented in Table 5.

Table 5. Results of ore roasting kinetics, Experiment No. 3, Initial vanadium content: 4500 g/t, temperature: 700°C.

No	roasting time, min	Charge mass, g	Incinerated mass, g	Ash content, %
1	50	105	99.46	94.72
2	150	105	97.35	92.71
3	200	105	92.75	88.33
4	240	105	91.62	87.26
5	300	105	90.85	86.52

Table 6. Results of X-ray phase analysis of the mineralogical composition of ores after heap burning.

Minerals	Quantity	P_{CO}
Quartz	47.5	0.7
Anorthite	34.3	0.8
Anhydrous gypsum	1.6	0.2
Hematite	4.3	0.3
$AlFeO_3$	3.4	0.4
Muscovite 2M1	8.1	0.5
Sodium vanadate	0.5	0.2
Scheelite	0.3	0.0

When we roasted the ore at 700°C, the calcine turned gray. We stirred the mixture every 20-30 minutes. The calcine particles did not stick together. After roasting, we obtained the calcine and subjected it to selective leaching with water and sulfuric acid. The obtained calcine was examined using X-ray phase analysis to determine its mineralogical composition and evaluate the effectiveness of the calcination process. The results of the diffractogram analysis of the powdered calcine show that iron sulfide minerals are oxidized to form hematite. Therefore, the research suggests processing the calcine with water and sulfuric acid to expose the metal surfaces. We confirmed through X-ray phase analysis that the expected sodium vanadate (in the amount of 0.5%) was formed during the roasting process, which appears as a green light peak with an intensity of 5000 in three histograms of the diffractogram (the diffractogram is shown in Figure 3, and the mineralogical composition is presented in Table 6).

The presence of scheelite in the amount of 0.3% also indicates the formation of sodium wolframite after calcination. Calcium silicate minerals (in the form of anorthite, gypsum, anhydrite) and anhydrous gypsum (with a total content of 35.9%) were previously identified as minerals that determine the complexity of the product. The semi-quantitative mineral composition, determined by the Rietveld analysis method, is presented in Table 6, which describes the mineral composition of the calcined product.

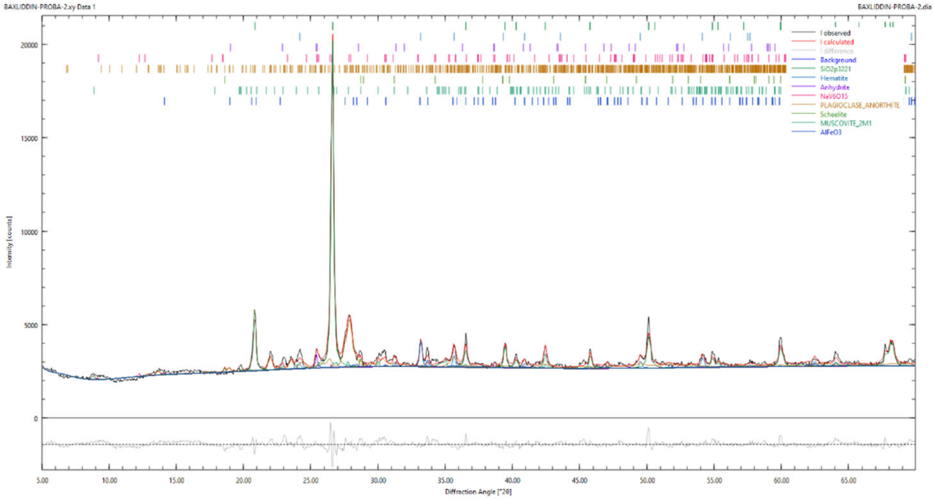


Fig.3. Diffractogram of powdered ash after the calcination process.

Table 7. Results of the kinetics of aqueous selective leaching of calcine: Initial vanadium content is 4500 g/t, t=80-90°C, S:L=1:3, calcine mass = 100 g.

No	**Selective dissolution time, min**	**Content of V in the solution, mg/L**	**Vanadium content in the cake, mg/kg**	**Degree of vanadium dissolution E, %**
1	40	505.5	298.35	33.7
2	60	546.0	286.2	36.4
3	80	655.5	253.35	43.7
4	100	742.5	227.25	49.5
5	120	802.5	209.25	53.5
6	140	802.5	209.25	53.5

Before leaching, we measure the mass of the calcine and send it for aqueous selective leaching. Then we add water until the solid to liquid ratio reaches S:L=1:3 and place it in a magnetic stirrer for selective dissolution. The mixture is stirred in the magnetic stirrer for 2 hours. The calcine obtained from roasting at 700°C was selectively leached in an experimental heating stirrer at a temperature of 80-90°C, with S:L=1:3, in an aqueous medium for 2 hours. The obtained results are presented in Table 7.

The experiment was conducted at various time intervals, with the highest degree of dissolution achieved within 2 hours, as further increases in time did not affect the dissolution rate. The selective water leaching of the calcine is illustrated by the curve in Figure 4 [6].

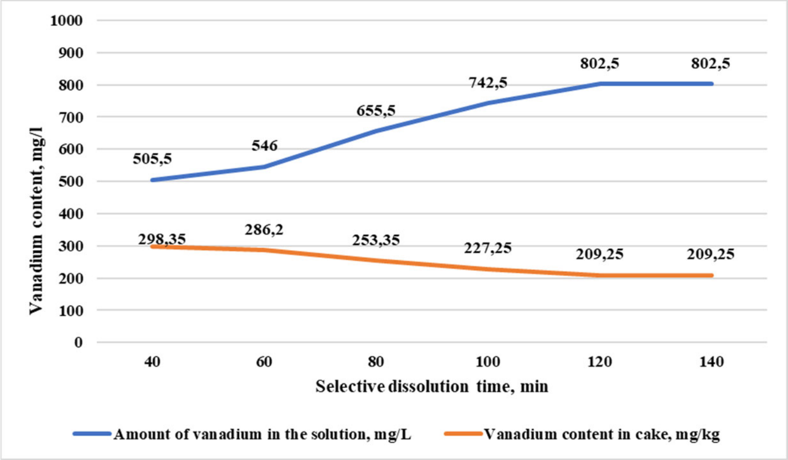


Fig. 4. Graph showing the relationship between vanadium content in the solution and cake as a function of selective leaching time in water.

Due to the low vanadium content resulting from selective dissolution in water, we selectively dissolved the remaining cake in a sulfuric acid solution. For this, we prepared a sulfuric acid solution with a concentration of 55 g/l and conducted selective dissolution for 2 hours at a temperature of 45°C with a liquid to solid ratio of 1:3. The cake formed from the selective dissolution in water of the calcine obtained by firing at 700°C was then selectively dissolved in a magnetic stirrer at a temperature of 45°C, with a liquid to solid ratio of 1:3, in a weakly acidic medium for 2 hours. The obtained results are presented in Table 8 below.

Table 8. Results of sulfuric acid selective leaching kinetics: The vanadium content in the cake is 209.25 mg, S:L=1:3, C (H_2SO_4) = 55 g/l.

No	Selective dissolution time, min	Content of V in the solution, mg/L	Vanadium content in the cake, mg/kg	Degree of vanadium dissolution E, %
1	40	401.1	88.9	57.5
2	60	458.9	71.6	65.8
3	80	538.5	47.7	77.2
4	100	592.2	31.6	84.9
5	120	647.3	15.1	92.8
6	140	647.3	15.1	92.8

It was observed that even when the selective leaching process time was increased beyond 120 minutes, the degree of vanadium dissolution into the solution did not increase. For this reason, the duration of the selective leaching process was chosen to be 120 minutes. Precipitation of vanadium from the sulfate vanadium that had entered the solution composition was carried out with alkaline solutions in the form of ammonium vanadate. As the concentration of NH_4OH increases in the solution, the solubility of NH_4VO_3 decreases [7]: $2VOSO_4 + 2NH_4OH = 2NH_4VO_3 + 2SO_2 + H_2O$

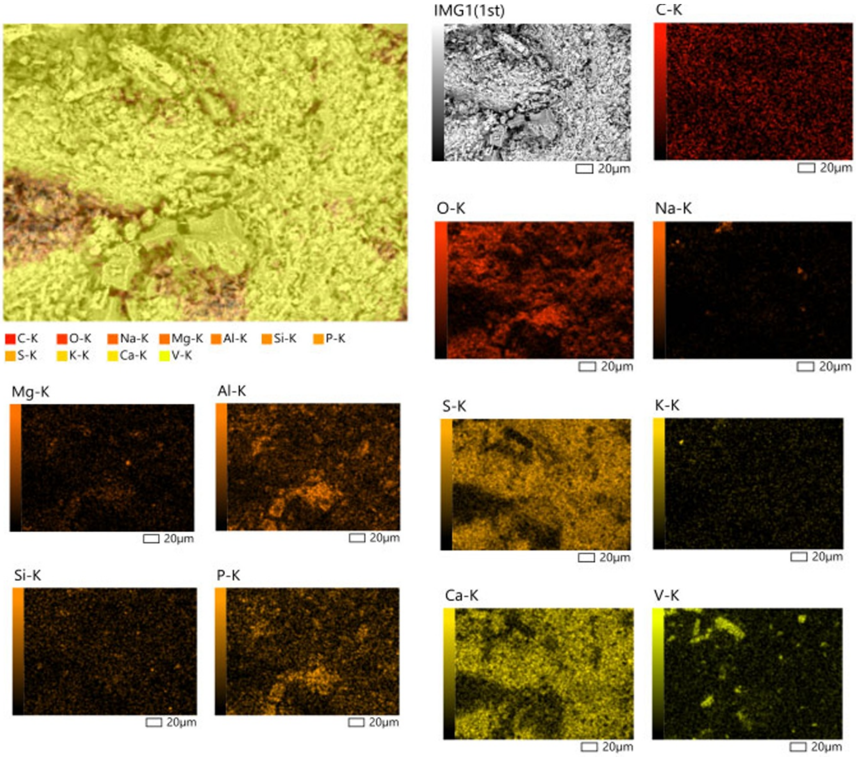
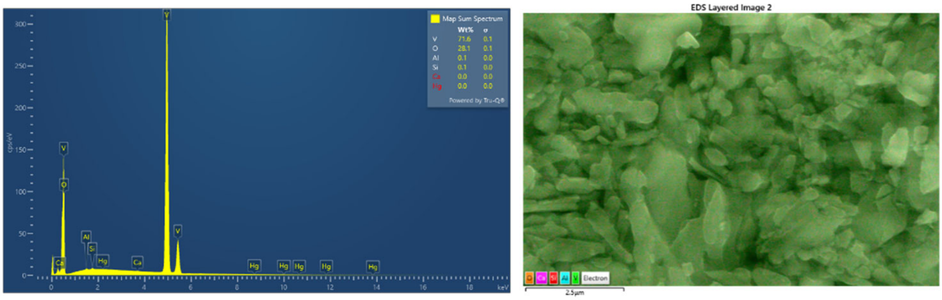


Fig. 5. Results of SEM analysis on the purity of V_2O_5 obtained from the Sijjak deposit.



Map Sum Spectrum

	Wt%	σ
V	71.6	0.1
O	28.1	0.1
Al	0.1	0.0
Si	0.1	0.0
Ca	0.0	0.0
Hg	0.0	0.0

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Fig. 6. SEM analysis images of V_2O_5 obtained using the proposed technology (magnified 10,000 times).

At a concentration of 85-100 g/l of NH_4OH in the solution, vanadium precipitates almost completely. At a precipitation temperature of 50-60°C, with a V_2O_5 concentration of 45-60 g/l and under stirring conditions, coarse-crystalline, easily filterable NH_4VO_3 is formed. The high-quality vanadium precipitate is filtered and dried at a temperature of 110-130°C. Ammonium vanadate is obtained as a dry powder, which is then subjected to thermal decomposition to produce vanadium pentoxide. The thermal decomposition process proceeds according to the following reaction [8]: $2NH_4VO_3=2NH_3+V_2O_5+H_2O$

After heat treatment, pure V_2O_5, necessary for the production of catalysts, pure metals, and alloys, is obtained. The vanadium pentoxide (V_2O_5) produced through this technology is analyzed using a scanning electron microscope to determine its purity level and the quantity of the compound in the product. The quality of the product is then verified by determining its dimensions (refer to Figures 5, 6 and Table 9).

The results of studying V_2O_5 powders using scanning electron microscopy and energy-dispersive spectroscopy demonstrate that the obtained powder is of high purity (refer to Table 13), with the proportion of vanadium constituting 71.6% (Figures 5-6).

Table 9. Results of the energy-dispersive analysis of V_2O_5 powder extracted from the ores of the Sijjak deposit.

Element	Signal Type	Line	Apparent Concentration	k Ratio	Wt%	Wt% Sigma	Standard Name	Factory Standard
O	EDS	K series	5.35	0.01800	28.12	0.10	SiO_2	Yes
Al	EDS	K series	0.07	0.00054	0.13	0.00	Al_2O_3	Yes
Si	EDS	K series	0.07	0.00053	0.10	0.00	SiO_2	Yes
Ca	EDS	K series	0.03	0.00030	0.03	0.00	Wollastonite	Yes
V	EDS	K series	53.96	0.53963	71.61	0.10	V	Yes
Hg	EDS	M series	0.00	0.00000	0.00	0.02	HgTe	Yes
Total					100.00			

The results of the spectral analysis also confirmed the accuracy of the aforementioned findings. Spectral analyses revealed that the purity level of the semi-finished product V_2O_5 is higher than 90%, and we can observe that residual amounts of calcium, aluminum, potassium, and silicon oxides remain as additional components in the product.

Table 10. Results of the analysis to determine the purity level of vanadium pentoxide.

No	Name of the sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14
		Si	**Al**	**Ca**	**Na**	**K**	**Fe**	**Mg**	**P**	**Ba**	**Sr**	**B**	**Mn**	**V**	**Ti**
		Mass percentage													
1	V_2O_5 after tempering	1.5	7	0.8	4	0.1	0.3	0.7	-	-	0.03	-	0.03	45	0.03
No	Name of the sample	**Cr**	**Pt**	**Pd**	**Os**	**Ir**	**Au**	**Ag**	**Cu**	**Pb**	**Zn**	**As**	**Bi**	**Ni**	**Co**
		Mass percentage													
		15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	V_2O_5 after tempering	-	-	-	-	-	-	-	0.05	-	0.04	-	-	0.004	-
No	Name of the sample	29	30	31	32	33	34	35	36	37	38	39	40	41	42
		Sb	**Hg**	**Mo**	**W**	**Sn**	**Be**	**Ta**	**Nb**	**Li**	**C**	**La**	**Y**	**Gd**	**Ib**
		Mass percentage													
1	V_2O_5 after tempering	-	-	0.0004	-	-	-	-	-	-	-	-	-	-	-
No	Name of the sample	43	44	45	46	47	48	49	50	51	52	53	54	-	-
		Zr	**Hf**	**Re**	**Sc**	**Te**	**Cd**	**In**	**Tl**	**Ga**	**Ge**	**U**	**Th**	**-**	**-**
		Mass percentage													
1	V_2O_5 after tempering	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Based on the results of the conducted research, a recommended technological scheme for extracting vanadium from the ores of the Sijjak deposit in the form of semi-finished products and alloys was developed (Figure 7).

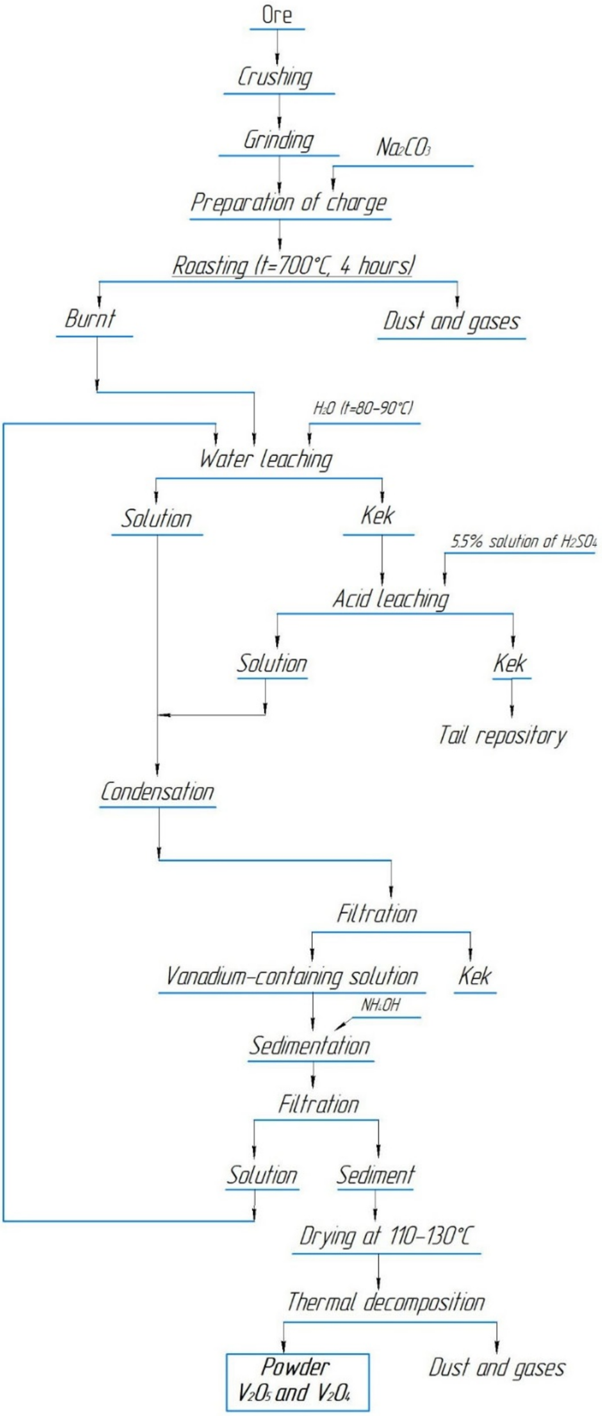

Fig. 7. Recommended technological scheme for extracting vanadium from the ores of the Sijjak deposit.

Optimal parameters for each process of the developed technology according to scheme 7 were established, including their dependence on firing temperature and time, as well as the relationship between solvent concentrations and process duration in selective leaching processes. Additionally, the modes for maximum vanadium extraction were studied.

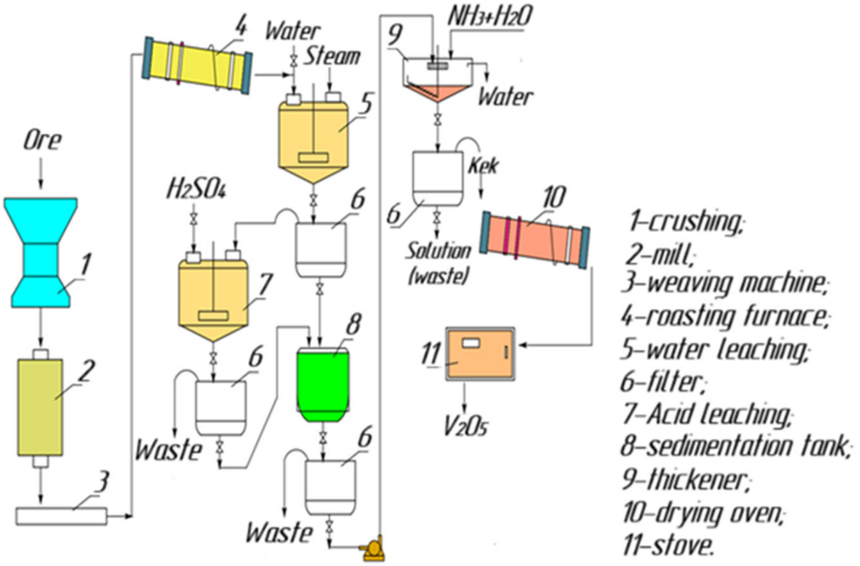

Fig. 8. Schematic diagram of the equipment chain for extracting vanadium from ores of the Sijjak deposit.

Semi-industrial pilot tests were conducted according to the developed technological scheme, and appropriate certificates were obtained due to the high quality of the resulting products. The chain diagram of the developed equipment is shown in Figure 8. A material balance has been developed based on the technological description of extracting vanadium in the form of pentoxide powder from the ores of the Sijjak deposit, and it is presented in Table 11.

Table 11. Calculated material balance for the extraction of vanadium from 1000 kg of ore from the Sijjak deposit (by metal content).

No	Products	Quantity	Unit of measurement	V quantity, g/t, mg/L	Mass V, g	Degree of separation, %	
						Private divorce (E)	Total separation (ε)
1	**Roasting (in hot ashes)**						
	Loaded:						
	Ore	1000	kg	4500	4500	100	100
	Sodium (Na_2CO_3)	50	kg	-	-	-	-
	Total:	1050	kg	4300	4500	100	100
	Received:						
	Burnt	908.5	kg	4354	3956	87.9	87.9
	Gases+dust	141.5	kg	3845	544	12.1	12.1
	Total:	1050	kg	-	-	-	-

Table 11. Calculated material balance for the extraction of vanadium from 1000 kg of ore from the Sijjak deposit (by metal content) (continued).

2.	**Selective dissolution in water**						
	Loaded:						
	Burnt	908.5	kg	4354	3956	87.9	87.9
	Recycled solution	2725.5	l	-	-	-	-
	Total:	3634	kg	4354	3956	87.9	87.9
	Received:						
	Solution	2727.9	l	776	2117	53.5	47.1
	Revenge	906.1	kg	2030	1839	46.5	40.8
	Total:	3634		4354	3956	100	87.9
3.	**Selective leaching with sulfuric acid**						
	Loaded:						
	Revenge	906.1	kg	2030	1839	100	40.8
	H_2SO_4 solution	2718.3	l	-	-	-	-
	Total:	3624.4	kg	2030	1839	100	40.8
	Received:						
	Solution	2720.4	l	627.3	1706.6	92.8	37.8
	Revenge	904	kg	14.65	132.4	7.2	3.0
	Total:	3624.4		-	1839	100	40.8
4.	**Submersion**						
	Loaded:						
	Vanadium solution	5448.3	l	702	3824	100	84.9
	NH_4OH solution	2724.1	l	-	-	-	-
	Total:	8172.4		-	3824	100	84.9
	Received:						
	Sediment	10.9	kg	34.4*	3747.5	98	83.2
	Solution	8161.5	l	9.4	76.5	2	1.7
	Total:	8172.4		-	3824	100	84.9
5.	**Thermal decomposition**						
	Loaded:						
	Sediment	10.9	kg	34.4*	3747.5	100	83.2
	Total:	10.9	kg	34.4*	3747.5	100	83.2
	Received:						
	V_2O_5 and V_2O_4 powder	7.2	kg	51.2*	3687.5	98.4	81.9
	Gases and dust	3.7	kg	1.62*	60	1.6	1.3
	Total:	10.9	kg	-	3747.5	100	83.2

* the vanadium content is expressed as a percentage.

Based on the calculated material balance for vanadium extraction from Sijjak deposit ores, the overall vanadium recovery rate was 81.9%, while the vanadium extraction rate into solution during the general selective leaching processes reached 84.9%.

4 Conclusion

The study of the firing process was conducted at various temperatures within the range of 600-850°C, with time intervals of 4-5 hours. The optimal temperature regime for roasting was determined to be 700°C, carried out for 4 hours with the addition of sodium carbonate as a binding material for vanadium at 5% of the initial material's mass, resulting in a calcine yield of 86.52%. As a result of roasting, the mass of the initial charge decreased compared to the mass of the calcine, which was verified by determining the decomposition of carbonaceous substances associated with the temperature regime.

The investigation of the process of selectively dissolving the calcine into an aqueous solution was performed using a magnetic stirrer, heating the solution to 80-90°C at a solid-to-liquid ratio of 1:3 for 2 hours, resulting in a vanadium solubility rate of 53.5%. The optimal parameters for sulfuric acid leaching of the calcine were determined by heating at 45°C in a weakly acidic medium with an H_2SO_4 concentration of 55 g/l for 2 hours at a solid-to-liquid ratio of 1:3. As a result, the vanadium solubility rate reached 92.8%.

The precipitation of vanadium in the form of ammonium vanadate from sulfuric acid solutions was studied. Vanadium was precipitated from the solutions using ammonia; with an increase in excess ammonia in the solution, the solubility of NH_4VO_3 decreased. At a precipitation temperature of 50-60°C, a vanadium concentration of 45-60 g/l V_2O_5, and with stirring, a coarse-crystalline precipitate of NH_4VO_3 that is easily filtered was obtained.

Based on the research results, a technological scheme was developed, incorporating pyrometallurgical methods and a combination of hydrometallurgical processing of calcine to produce high-quality intermediate products of vanadium pentoxide with a purity of over 92%, achieving a total vanadium recovery rate of 81.9% from the ores.

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