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Satbayev University

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ИЗВЕСТИЯ

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RECYCLING OF CHRYSOTILE-ASBESTOS PRODUCTION WASTE WITH EXTRACTING MAGNESIUM AND OBTAINING A FERROALLOY AND CALCIUM SILICATES

Abstract. The article considers the results of studies on the processing of a chrysotileasbestos production waste by a pyrometallurgical method. The studies included thermodynamic modeling using the HSC-6.0 software package, based on the minimum Gibbs energy principle, together with the second-order rotatable designs (Box-Hunter plans), as well as electric melting of the waste in a single-electrode arc furnace. Based on the results of the research, it was found that, in equilibrium conditions, 92-98% of magnesium is distilled off from the waste in the presence of 31.8-33.9% of calcium carbide at a temperature of 1725-1883 °C and a pressure of 0.1 bar, 80-85% of CaO turn into calcium silicates (mainly into $2CaO \cdot SiO_2$); only 8.7-12.5% of silicon is extracted in FS25 grade ferrosilicon; a decrease in pressure from 0.1 to 0.01 bar makes it possible to reduce the temperature of complete distillation of magnesium to 1600°C, and the transition of calcium to calcium silicates to 1300°C; at the electric melting of the chrysotile-asbestos waste at the presence of coke and steel shavings, a FS25 grade ferroalloy is formed with the extraction of 74-85% of silicon in the alloy and >94% of magnesium in a gas phase.

Key words: chrysotile-asbestos, pyrometallurgy, waste, thermodynamics, ferroalloy, magnesium, silicates.

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АСБЕСТ ХРИЗОТИЛ ҚАЛДЫҚТАРЫН ҚАЙТА ӨҢДЕУ МАГНИЙ АЛАТЫН ӨНДІРІС ЖӘНЕ ФЕРРОҚОРЫТПА МЕН КАЛЬЦИЙ СИЛИКАТТАРЫН АЛУ

Аннотация. Мақалада хризотил-асбест өндірісінің қалдықтарын пирометаллургиялық әдіспен өңдеуді зерттеу нәтижелері келтірілген. Зерттеулер Гиббс энергиясының минималды принципіне негізделген HSC-6.0 бағдарламалық кешенін қолдана отырып, термодинамикалық модельдеу әдісімен екінші ретті ротатабельді жоспарлаумен (бокс-Хантер жоспары), сондай-ақ бір электродты доғалы пеште қалдықтарды электрмен балқыту арқылы жүргізілді. Зерттеулер нәтижесінде: тепе-теңдік жағдайында қалдықтардан 1725–1883°C кезінде 31,833,9% кальций карбидінің қатысуымен және 0,1 бар қысымда 92–98% магний алынады, 80–85% CaO кальций силикаттарына (негізінен $2CaO \cdot SiO_2$) ағынды өнімге ауысады; ФС25 маркалы ферросилиций тек 8,7-12,5%-ға ауысады. Кремний; қысымның 0,1-ден 0,01 барға дейін төмендеуі магнийді толық айдау температурасын 1600°C дейін, ал кальцийдің кальций силикаттарына ауысуын 1300°C дейін төмендетуге мүмкіндік береді; қалдықтарды кокс және болат жаңқаларының қатысуымен электрмен балқыту кезінде газ фазасына 74–85% кремний және 94% магний алу арқылы ФС25 маркалы ферроқорытпа түзіледі.

Түйін сөздер: хризотил-асбест, пирометаллургия, қалдықтар, термодинамика, ферроқорытпа, магний, силикаттар.

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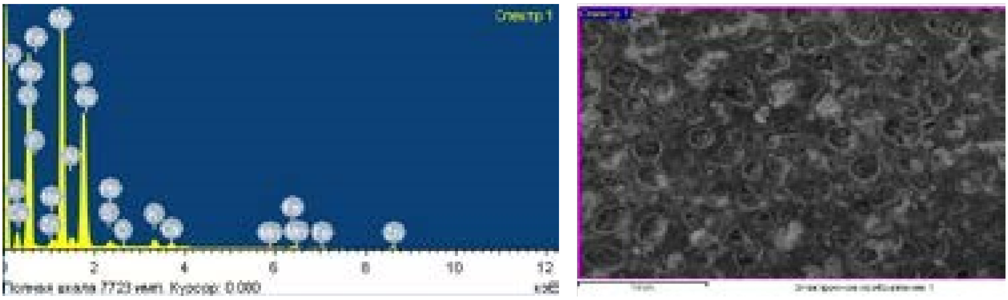
ПЕРЕРАБОТКА ОТХОДОВ ХРИЗОТИЛ АСБЕСТОВОГО ПРОИЗВОДСТВА С ИЗВЛЕЧЕНИЕМ МАГНИЯ И ПОЛУЧЕНИЕМ ФЕРРОСПЛАВА И СИЛИКАТОВ КАЛЬЦИЯ

Аннотация. В статье приводятся результаты исследований переработки отходов хризотил-асбестового производства пирометаллургическим методом. Исследования проводились методом термодинамического моделирования с использованием программного комплекса HSC-6.0, основанного на принципе минимума энергии Гиббса совместно с рототабельным планированием второго порядка (план Бокса-Хантера), а также электроплавкой отходов в одноэлектродной дуговой печи. В результате исследований установлено, что: в равновесных условиях из отходов в присутствии 31,8-33,9% карбида кальция при

1725-1883°C и давлении 0,1 бар происходит отгонка 92–98% магния, переход 80–85% CaO в силикаты кальция (преимущественно в $2CaO \cdot SiO_2$) в поточный продукт; ферросилиций марки ФС25 переходит только 8,7-12,5% кремния; уменьшение давления от 0,1 до 0,01 бар позволяет снизить температуру полной отгонки магния до 1600°C, а перехода кальция в силикаты кальция до 1300°C; при электроплавке отходов в присутствии кокса и стальной стружки образуется ферросплав марки ФС25 с извлечением в сплав 74–85% кремния и >94% магния в газовую фазу.

Ключевые слова: хризотил-асбест, пирометаллургия, отходы, термодинамика, ферросплав, магний, силикаты.

Introduction. The main components of the chrysotile-asbestos waste (CAW) are MgO (41-50%) and SiO_2 (30-37%). In addition, the waste contains 2.6-3.8% of Al_2O_3, 1.2-1.4% of Fe_2O_3, 2.3-2.4% of $\sum K_2O+Na_2O$, 1.1-1.4% of CaO, 0,8-1.4% of ZnO, 1.01.2% of PbO, as well asinsignificant quantities of substances containing sulfur, chlorine, fluorine, manganese (Figure 1).



Element	O	F	Na	Mg	Al	Si	S	Cl	K	Ca	Mn	Fe	Zn	Pb
Content, %	46,63	1,25	0,74	27,61	1,25	16,77	0,6	0,15	1,22	0,64	0,27	0,85	1,1	0,93

Figure 1 – Results of SEM analysis of the Kostanay Minerals JSC chrysotile-asbestos waste

According to the data of The National Center for Comprehensive Processing of Mineral Raw Materials of the Republic of Kazakhstan, these wastes also contain 0.20.3% of NiO. In accordance with (Production and turnover of the commodity item HS 2524 “Asbestos”), annually JSC “Kostanay Minerals” mines 5 million tons of chrysotileasbestos; 92% of this quantity (4.6 million tons) is wasted that leads to the annual loss of 1.16 m. t. of magnesium, 0.73 m. t. of silicon, 45.0 ths. t. of zinc, 42.0 ths. t. of lead, 9.0 ths. t. of nickel on average. There are known methods for processing chrysotile asbestos waste using acid leaching (Shayakhmetova et al., 2019: 3; Kobzhasov et al., 2009: 5; Wang et al., 2006; Baysanov et al., 2018: 11; Dikanbayeva et al., 2021: 7) to obtain only one element: silicon (Jafarov, 2003: 8), magnesium (Baigenzhenov et al., 2014: 36; Bedelova et al., 2015: 5; Kobzhasov et al., 2009: 5;

Foresti et al., 2009: 10). However the CAW processing should be comprehensive to extract not only magnesium and silicon, but also non-ferrous metals.

The authors (Utkin, 2004: 442; Aueshov et al., 2020: 1215) suggest several thermal methods for extracting magnesium from magnesite and dolomite, which are based on the following reactions:

$MgO + C = Mg_{(g)} + CO;$ (1) $2MgO + Si = 2Mg_{(g)} + SiO_2;$ (2) $3MgO + CaC_2 = 3Mg_{(g)} + CaO + 2CO;$ (3) $3MgO + Al = 3Mg_{(g)} + Al_2O_3;$ (4)

$$2MgO + 2CaO + SiO_2 = 2Mg_{(g)} + (2CaO)\cdot SiO_2 + 2CO; \quad (5)$$

$$2MgO + 2CaO + FeSi_2 + Al_2O_3 = 2Mg_{(g)}+(2CaO)\cdot SiO_2\cdot Al_2O_3+FeSi. \quad (6)$$

The effect of temperature on ΔG° of these reactions is shown in Table 1.

Table 1 – Effect of temperature on ΔG° (kcal)* of some reactions of obtaining magnesium

Reaction	Temperature, °C									
	1300	1400	1480	1600	1800	1846	1853	1900	1903	2000
1	157,9	128,7	82,3	70,7	13,2	0,0	-20	-15,3	-16,2	-43,7
2	183,7	159,2	142,1	116,3	73,8	63,6	62,2	52,4	51,9	31,0
3	357,6	292,2	279,8	162,3	33,7	4,4	0,0	-30,1	-32,0	-93,7
4	51,9	22,6	0,0	-35,6	-93,0	-105,4	-107,6	-121,6	-122,4	-149,9
5	6,1	0,0	-6,5	-16,2	-31,9	-35,5	-36	-39,7	-40,3	-47,6
6	0,0	-27,6	-52,7	-90,4	-153,4	-167,8	-169,8	-184,7	-185,7	-215,9

*The calculation was performed using the HSC-6 software package (the Equilibrium Compositions subprogram) (Roine, 2002)

It can be seen that at normal atmospheric pressure silicon does not reduce magnesium up to 2000°C. The temperature of the beginning of the formation of gaseous magnesium is 1300°C for reaction 6 and 1853 °C for reaction 3. In accordance with the Le Chatelier principle, to reduce the temperature of the reactions, they should be carried out at a low residual pressure. For example, in the silicothermic production of magnesium using ferrosilicon, the residual pressure is 2.5-4 kPa (Overview of Chrysotile Asbestos in Kazakhstan).

Industrial technologies allow you to produce magnesium from raw materials containing MgO or MgO and CaO. Chrysotile-asbestos industrial waste products, in addition to MgO, contain a significant amount of $SiO_2$and an insignificant amount of CaO. Therefore, it is necessary to develop a technology for the extraction of magnesium from CAW, taking into account the presence of silica in it. The purpose of this work was to provide a thermodynamic and experimental substantiation of a technology that allows one to extract magnesium from CAW and convert silicon either into marketable products or into artificial raw materials for manufacturing some end products.

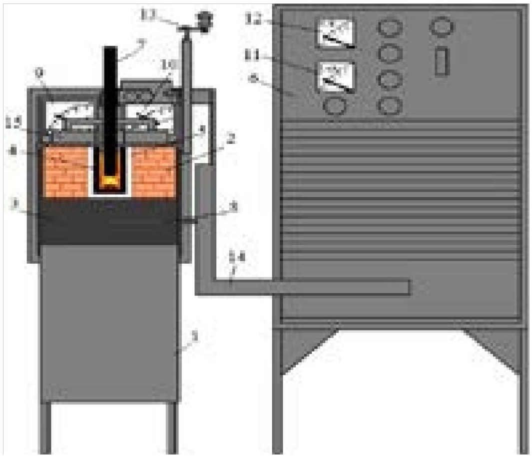
Methods and materials. The research techniques included thermodynamic modeling of the process and experimental electric smelting of the CAW in an ore-thermal furnace.

Thermodynamic modeling of the obtaining gaseous magnesium from the CAW was implemented using the HSC-6 Chemistry software package developed by the Finnish metallurgical company Outokumpu [Roine, 2002]. Calculation of the equilibrium conditions by the HSC-6 program is based on the principle of minimum Gibbs energy, taking into account the activities of substances (subprogram Equilibrium Compositions). The error of calculations by the HSC-6 software package is no more than 2-4%.

The modeling was carried out using the second-order rotatable planning (Akhnazarova et al., 1985: 327; Shevko et al., 2021: 9) with the construction of volumetric and planar images of technological parameters (Ochkov, 2009: 512; Udalov, 2012: 187).

I

II



1 – furnace casing, 2 – chromium magnesite lining, 3 – carbon graphite hearth, 4 – graphite crucible, 5 – carbon graphite chips, 6 – transformer TDZhF-1002, 7 – graphite electrode, 8 – bottom current lead,9-12 – control ammeters and voltmeters, 13 – electrode movement mechanism, 14 – flexible part of the short network, 15 – furnace cover

I – general view, II – sketch of the furnace with nodes

Figure 2 – Laboratory installation with a single-electrode arc furnace

The electric melting of the CAW was conducted in a single-electrode arc furnace (Figure 2). The bottom electrode was made of a graphite block, and the top electrode (d=3cm) was made from graphite. A graphite crucible (d=6cm, h=12cm) was placed on the hearth. The space between the crucible and the chromium-magnesite lining was filled with graphite chips. The process was carried out in an air atmosphere. Before the melting, the crucible was heated by an arc for 20-25 min. After the heating, the first portion of a charge (200 g) was loaded into the crucible. It was melted for 5-6 min, and then the rest of the charge (200 g) was loaded and melted for 25-30 min. During the melting period, the current strength was 250-400A; the voltage was 25-30V. Electricity to the furnace was supplied by a TDZhF-1002 transformer. The required power was maintained by a terristor regulator. The current strength was controlled with a Tangen 42L6 ammeter (accuracy class 1.5), and the voltage was controlled with a Chint 42L6 voltmeter (accuracy class 1.5). After the end of the electric smelting, the furnace was cooled for 6 hours. The graphite crucible was removed from the furnace and broken. The analysis of initial raw materials andresulting ferroalloys was carried out using a scanning electron microscope (SEM) JSM-6490LM (Japan); the SEM analysis error is <1%. The silicon content in the alloys was determined using an atomic absorption spectrometer ContrAA-300 (Germany) and also by pycnometric methods according to State Standard 22524-77.

When conducting the research, we used not only pure substances (CaO, SiO_2, CaC_2), but also a chrysotile asbestos waste containing, wt. %: 47 MgO, 43 SiO_2, 5.7 Fe_2O_3, 2 FeO, 1.5 Al_2O_3, 0.5 CaO, 0.3 NiO; coke contained 86% of C, 4.9% of SiO_2, 2.7% of Al_2O_3, 1.8% of CaO, 0.9% of Fe_2O_3, 0.8% of MgO, 1.1% of H_2O, 0.7% of S, 0.4% - others; the concentration of iron in the steel shavings was 98% (the rest: C, Si, Mn). Technical calcium carbide contained 62% of CaC_2, 37% of CaO and 11% of impurities.

Results and discussion. In contrast to the known methods, we studied the possibility of obtaining gaseous magnesium from the CAW using iron, carbon and calcium carbide with simultaneous producing iron silicides, belite and calcium aluminosilicate.

Reactions in question:

$$6MgO + 2CaC_2 + SiO_2 = 6Mg_{(g)} + (2CaO)\cdot SiO_2 + 4CO; \quad (7)$$

$$6MgO + 2CaC_2 + SiO_2 + Al_2O_3 = 6Mg_{(g)} + (2CaO)\cdot SiO_2\cdot Al_2O_3 + 4CO; \quad (8)$$

$3MgO + CaC_2 + SiO_2 = 3Mg_{(g)} + CaO\cdot SiO_2 + 2CO$; (9) $MgO + 2SiO_2 + Fe + 5C = FeSi_2 + Mg_{(g)} + 5CO$; (10) $MgO + SiO_2 + Fe + 3C = FeSi + Mg_{(g)} + 3CO$; (11)

$$MgO + SiO_2 + 3Fe + 3C = Fe_3Si + Mg_{(g)} + 3CO; \quad (12)$$

$$MgO + 6SiO_2 + Fe_3O_4 + 17C = FeSi_2 + Mg_{(g)} + 17CO. \quad (13)$$

The data in Table 2 show the effect of temperature on ΔG° of reactions (7-13) of formation of ferroalloys, belite, calcium aluminosilicate and gaseous magnesium from the CAW.

Table 2 – Effect of temperature on ΔG° (kcal) of reactions (7-13).

Reaction	Temperature, °C											
	1300	1400	1437	1600	1622	1640	1688	1710	1713	1729	1800	1900
7	570	436,9	392,4	171,3	141,2	117,8	53,9	25,5	5,9	0	-92,9	-223,8
8	544,8	412,0	363,1	148,3	119,8	95,6	32,7	3,1	0	-32,7	-112,8	-242,2
9	63,8	48,1	26,7	17,0	13,8	11,2	4,2	0	-0,8	-2,9	-13,8	-29,0

10	365,1	270,1	234,8	81,7	61,6	43,5	0	-20,7	-23,5	-38,7	-103,5	-194,9
11	219,7	157,5	135,2	26,3	12,4	0	-30,9	-45,1	-47,1	-57,4	-103,2	-167,3
12	184,7	122,4	100,5	10,2	0	-8,2	-29,6	-39,1	-40,2	-46,1	-72,1	-97,8
13	397,9	107,6	0	-469,7	-530,6	-577,4	-715,4	-776,7	-785,0	-829,4	-1026,6	-1302

As it follows from Table 2, at normal pressure, the beginning of the simultaneous formation of gaseous magnesium and iron silicides in the presence of iron, magnetite and carbon occurs in a temperature area of 1437-1688°C, that is, at a lower temperature in comparison with the formation of silicates and calcium aluminosilicate (1710-1729°C). The thermodynamic modeling of the interaction in the CAW-C-Fe systems allowed us to establish that in order to extract 87% of magnesium into gas, the required temperature and pressure are 1514-1700°C and 0.01-0.0036 bar, respectively; at a temperature of 1200°C and a pressure of 0.001 bar, the extraction degree of silicon into an alloy is maximum (80.33%); regardless of the pressure, the resulting ferrosilicon contains 3133% of silicon.

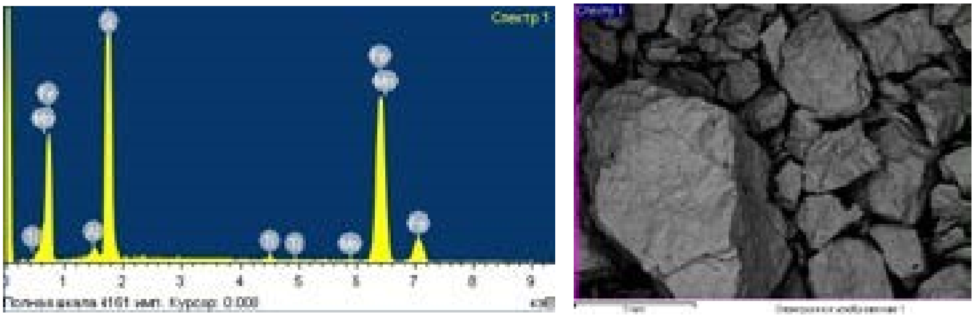
This article contains the results of studies of the simultaneous formation of gaseous magnesium, silicates, calcium aluminate, and iron silicides from the CAW in the presence of calcium carbide, as well as the experimental results of obtaining a ferroalloy from the CAW in the presence of carbon and iron and distillation ofmagnesium into a gas phase.

At the first stage, studies were carried out to obtain a ferroalloy from the CAW. The charge used for electric melting included 60% of CAW, 22% of coke, and 18% of steel shavings (the composition of the charge was calculated to obtain FS25 grade ferrosilicon). Photographs of the resulting ferroalloys are represented in Figure 3, and the SEM analysis results of the ferroalloys are shown in Figure 4.

I II III

I-II – lump ferroalloy, III – crushed ferroalloy

Figure 3 – Photographs of the ferroalloy produced from CAW

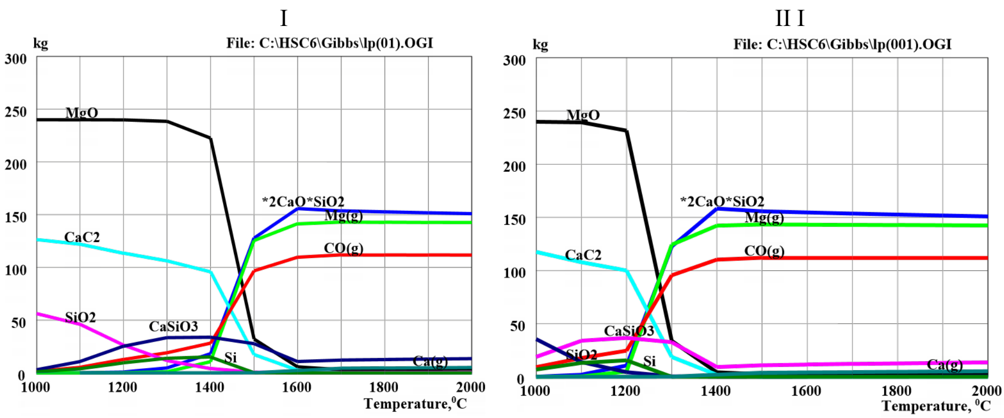


Element	Al	Si	Ti	Mn	Fe
Content, %	1,21	29,25	0,45	0,31	68,78

Figure 4 - Results of the SEM analysis of the ferroalloy

Pycnometric research of the resulting ferroalloys showed that their density is 5.186.43 g/cm^3. These ferroalloys can be attributed to FS25 grade ferrosilicon [20]. During the electric melting, from 74 to 83% of silicon is extracted into the alloy, and more than 94% of magnesium is extracted into a gas phase. Nickel containing in the CAW in quantity of 96% is also recovered into the alloy. The nickel content in the alloy was 0.23-0.32%. The relatively low extraction degree of silicon into the alloy is due to its transition into a gas phase as SiO(g) with the subsequent formation of micro silica. This is largely due to the fact that when using high-conductivity steel chips, the melting is carried out in the conditions of a high position of the electrodes, formation of an arc discharge in the furnace and the hot top. In a case of formation of a low-volatility silicon-containing product in the electric furnace, the silicon loss with the gas phase can be reduced. For this purpose, the second stage of the researchwas obtaining calcium silicate (belite $(2CaO)\cdot SiO_2$) from the CAW according to reaction 7. This compound can be used for manufacturing cement clinker.

The temperature and pressure effect on the formation of $(2CaO)\cdot SiO_2$ and gaseous magnesium in a $6MgO$-$2CaC_2$-SiO_2 system is represented in Figure 5.

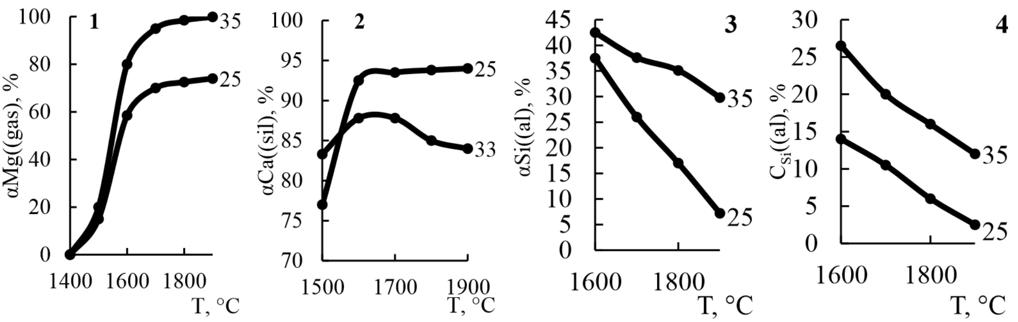


I – pressure of 0.1 bar, II – pressure of 0.01 bar
Figure 5 – Effect of temperature and pressure on the quantitative distribution of substances in a 6MgO-2CaC$_2$-SiO$_2$ system

The temperature of 1% formation of $Mg_{(gas)}$ and $(2CaO)\cdot SiO_2$ at a pressure of 0.1 bar is 1230 and 1318°C, respectively. At 1700°C, 98% of magnesium passes into a gaseous state and 89.3% of calcium – into $(2CaO)\cdot SiO_2$. Calcium carbide in the system completely reacted at a temperature of ≥1700°C. Reducing the pressure to 0.01 bar lowersthe temperature of >90% transition degree of calcium in $(2CaO)\cdot SiO_2$ (91.7%) to 1500 °C. In this case, 99.8% of Mg passes into the gas.

The next step was to study the effect of temperature and calcium carbide on the extraction degree of magnesium from the CAW in the gas ($\alpha_{Mg(gas)}$, %), calcium in calcium silicates ($\alpha_{Ca(sil)}$, %), silicon in the ferroalloy ($\alpha_{Si(al)}$, %) and on the concentration of silicon in the alloy ($C_{Si(al)}$, %) at a pressure of 0.1 bar. In view of the fact that the chrysotile-asbestos waste contains a small amount of CaO (p. 1), to obtain $(2CaO)\cdot SiO_2$, it is necessary additionally introduce calcium oxide into the charge. The charge used for the study (taking into account the additional input of CaO) contained, %: 47 MgO, 37.7 SiO_2, 5.7 Fe_2O_3, 2 FeO, 1.5 Al_2O_3, 39 CaO. The amount of calcium carbide was changed from 25 to 35% of the CAW mass.

Figure 6 represents the effect of temperature and the amount of calcium carbide on the technological parameters of the process under study. It should be noted that due to the presence of iron oxides in the CAW, part of the silicon in the system under consideration passes in the ferroalloy as iron silicides.



1 – $\alpha_{Mg(gas)}$, 2 – $\alpha_{Ca(sil)}$, 3 – $\alpha_{Si(al)}$, 4 – $C_{Si(al)}$
The numbers near the lines – the amount of calcium carbide, % of the CAW mass
Figure 6 – The effect of temperature and calcium carbide

on$\alpha_{Mg(gas)}$, $\alpha_{Ca(sil)}$, $\alpha_{Si(al)}$, $C_{Si(al)}$

As it follows from Figure 6, an increase in the amount of calcium carbide from 25 to 35% leads to an increase in $\alpha_{Mg(gas)}$, $\alpha_{Si(al)}$, $C_{Si(al)}$and a decrease in $\alpha_{Ca(sil)}$. In view of the ambiguity of the calcium carbide effect on the technological parameters, it is necessary to determine the conditions under which $\alpha_{Mg(gas)}$ and $\alpha_{Ca(sil)}$will be maximum, and $\alpha_{Si(al)}$– minimum. For this reason, furtherstudies were carried out using the secondorder rotatable designs followed by graphical optimization of the process parameters. The experiment planning matrix and the results are shown in Table 3.

Table 3 – The planning matrix and results on the effect of temperature (T, °C) and the amount of calcium carbide (CC, %) on the technological parameters

№	Variables				Technological parameters				Areas of the plan
	Code kind		Natural kind						
	X_1	X_2	T, °C	CC, %	$\alpha_{Mg(gas)}$	$\alpha_{Ca(sil)}$	$\alpha_{Si(al)}$	$C_{Si(al)}$	
1	+	+	33	1857	94,4	83,2	9,4	24,4	Nucleus
2	-	+	27	1857	89,7	88,0	19,0	47,7	
3	+	-	33	1643	82,3	90,7	4,2	12,8	
4	-	-	27	1643	70,3	92,8	13,0	32,4	
5	1,414	0	35	1750	91,5	86,8	4,0	11,3	Star points
6	-1,414	0	25	1750	66,6	91,0	15,8	47,1	
7	0	1,414	30	1900	97,5	74,2	17,5	47,0	
8	0	-1,414	30	1600	71,2	39,9	7,9	22,2	
9	0	0	30	1750	88,9	89,0	10,9	23,6	Center
10	0	0	30	1750	88,0	91,0	10,0	25,4	
11	0	0	30	1750	85,0	92,5	10,5	25,0	
12	0	0	30	1750	89,3	91,6	9,6	26,8	
13	0	0	30	1750	86,5	89,5	91	26,0	

Based on the data in Table 3, the following adequate regression equations were obtained:

$\alpha_{Mg(gas)}$ = -1470,45+1,34·T+19,32·CC-3,17·10^{-4}·T^2-0,11·CC^2-5,68·10^{-}3T·CC; (14)

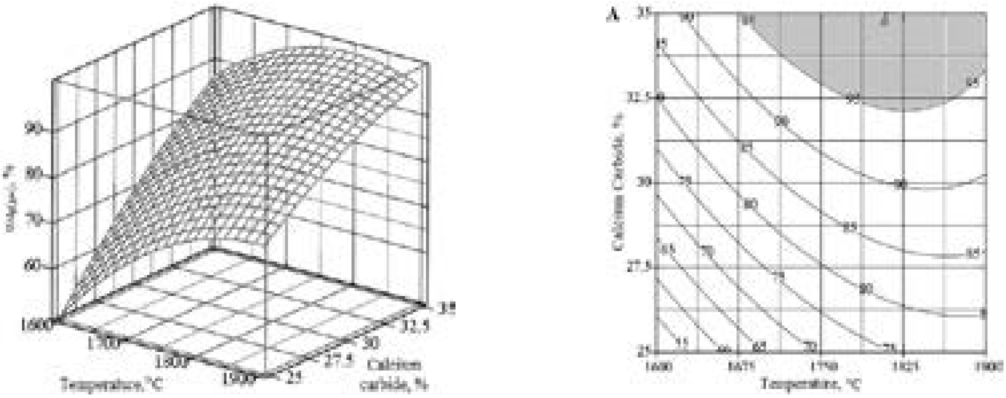
$\alpha_{Ca(sil)}$ = -318,04+0,158·T+20,57·CC-3,14·10^{-5}·T^2-0,309·CC-2,1·10^{-3}·T·CC; (15)

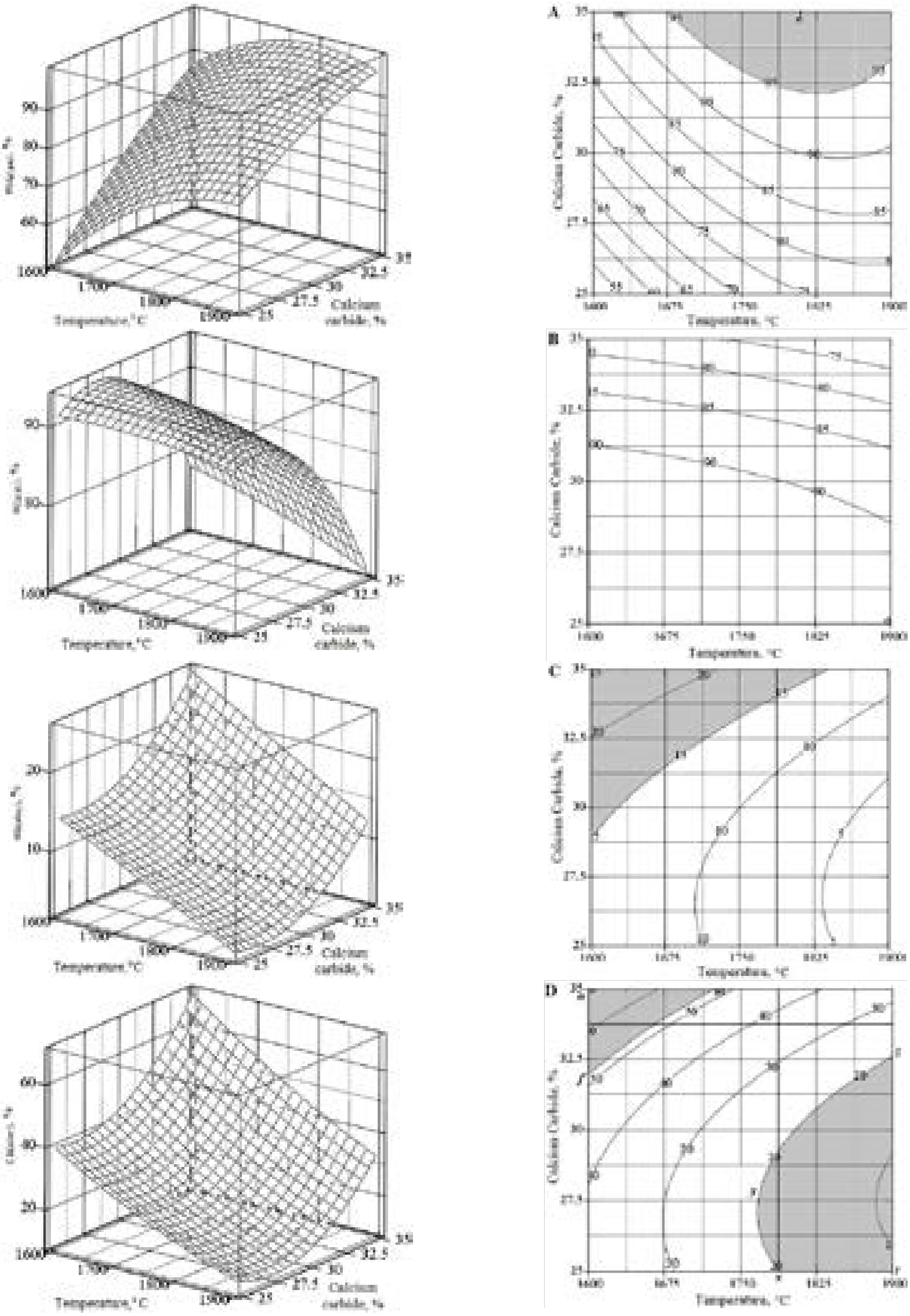
$\alpha_{Si(al)}$ = 145,21-11,6·10^{-3}·T-6,98·CC-3,06·10^{-6}·$T^{2+0,15}$·CC^2-6,23·10^{-4}·T·CC; (16)

$C_{Si(al)}$= 697,46-0,388·T-18,348·CC-1,04·10^{-4}·T^2+0,433·CC^2-2,88·10^{-3}·T·CC; (17)

Using equations 14-17, according to the method [16-19], volumetric and planar images of the temperature and calcium carbide effect on the technological parameters were constructed. Judging by Figure 7(A), $\alpha_{Mg(gas)}$from 95 to 98% (point a) can be reached in a temperature range of 1675-1900°C and 31.6-35% of calcium carbide. The transition degree of Ca in calcium silicates in this area does not exceed 85%. It becomes high (>90%) if the amount of calcium carbide is less than 31.6-28% (Figure 7 (B)). A side process in the production of $2CaO \cdot SiO_2$ is the formation of iron silicides, silicon and silicon carbide (Figure 5). A noticeable (from 15 to 25%) degree of silicon extraction into the alloy is observed in a temperature area of 1600-1837°C and 28.7-35% of carbide calcium (Figure 7(C)). The silicon concentration in the ferroalloy at a constant temperature increases with an increase in the amount of calcium carbide and is 50-70% at a temperature of 1600-1746°C and 31.6-35% of calcium carbide (Figure 7 (D), area fnm). With increasing the temperature, the silicon content in the alloy decreases, for example, <20% in a temperature range xyzt (1769-1900 °C and 25-32.5% of calcium carbide).

I II



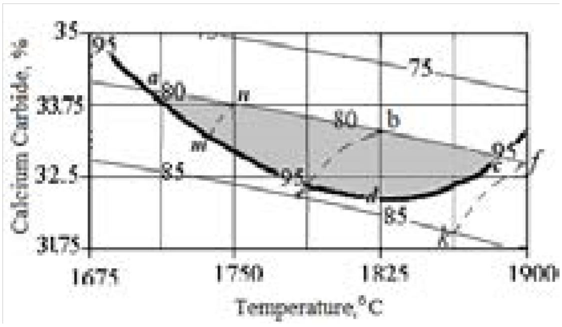


A, B, C – $\alpha_{Mg(gas)}$, $\alpha_{Ca(sil)}$, $\alpha_{Si(al)}$; D – $C_{Si(al)}$

Figure 7 – Volumetric (I) and planar (II) images of the temperature and calcium carbide effect on the technological parameters of interaction in the CAW-calcium carbide system

at a pressure of 0.1 bar

To determine the optimal conditions for the extraction of magnesium in gas, and calcium in silicates (temperature, amount of calcium carbide), we combined the information about these processes in one figure (Figure 8).



Lines: mn – $C_{Si(al)}$=41%, eb – $C_{Si(al)}$=29%, kf – $C_{Si(al)}$=21%
(——) - $\alpha_{Ca(sil)}$, (——) - $\alpha_{Mg(gas)}$, (——) - $C_{Si(al)}$

Figure 8 – Combined information on the effect of temperature and calcium carbide on $\alpha_{Mg(gas)}$, $\alpha_{Ca(sil)}$ and $C_{Si(al)}$

Optimum conditions were determined for$\alpha_{Mg(gas)}$>95% and $\alpha_{Ca(sil)}$from 80 to 85%. The area acd corresponding to these conditions is shown in Figure 8. The is o lines C_{Si} = 41, 29 and 21%, which make it possible to determine the conditions for the formation of graded ferrosilicon, are also plotted in the same figure (FS45 – area anm, FS25 – area ebcd). Table 4 represents the technological parameters in the shaded area.

Table 4 – Technological parameters of Figure 8

Point in figure8	T, °C	Calcium carbide, %	$\alpha_{Mg(gas)}$, %	$\alpha_{Ca(sil)}$, %	$\alpha_{Si(al)}$, %	$C_{Si(al)}$, %	Grade of ferrosilicon
a	1725	33,93	95,0	80,0	17,9	46,7	FS45
n	1750	33,75	97,22	80,0	16,1	41,0	FS45
b	1833	33,43	98,28	80,0	12,5	29,0	FS25
c	1883	32,87	95,0	80,0	8,7	21,0	FS25
d	1825	31,85	95,0	84,7	9,1	21,0	FS25
e	1787	32,08	95,0	84,9	9,5	29,0	FS25
m	1735	33,25	95,0	84,4	15,8	41,0	FS45

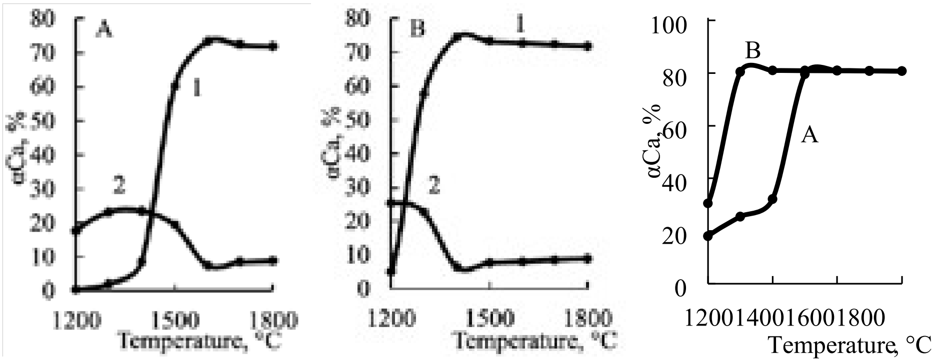
The purpose of the work was to maximize the magnesium distillation and to achieve the maximum extraction of calcium and silicon in $2CaO{\cdot}SiO_2$ and $CaO{\cdot}SiO_2$ with the simultaneous minimum extraction of silicon into ferroalloy. These conditions are met in the region bcde, in which $\alpha_{Mg(gas)}$ = 95.0-98.28%, $\alpha_{Ca(sil)}$ = 80-85%. In this case, the main part of silicon also passes into calcium silicates, and only 8.7-12.5% is extracted into the ferroalloy. The ferrosilicon formed in this region at 1787-1883°C contains 21-29%

of Si and, according to (Technical conditions 0820-011-14513884-2013), corresponds to FS25 ferrosilicon. The residue after the distillation of magnesium consists mainly of $2CaO \cdot SiO_2$, $CaO \cdot SiO_2$ (Table 5).

Table 5 – Phase composition of the residue (%) after the interaction of CAW with 33% of CaC_2

T, °C	Content,%						
	$2CaO \cdot SiO_2$	$CaO \cdot SiO_2$	SiO_2	CaO	MgO	CaC_2	Al_2O_3
1700	82,29	5,41	<0,1	7,87	2,94	abs.	1,43
1800	82,59	4,36	<0,1	10,26	1,60	abs.	1,47
1900	82,04	3,57	<0,1	12,22	1,14	abs.	1,49
2000	79,24	3,01	<0,1	14,33	0,89	abs.	1,52

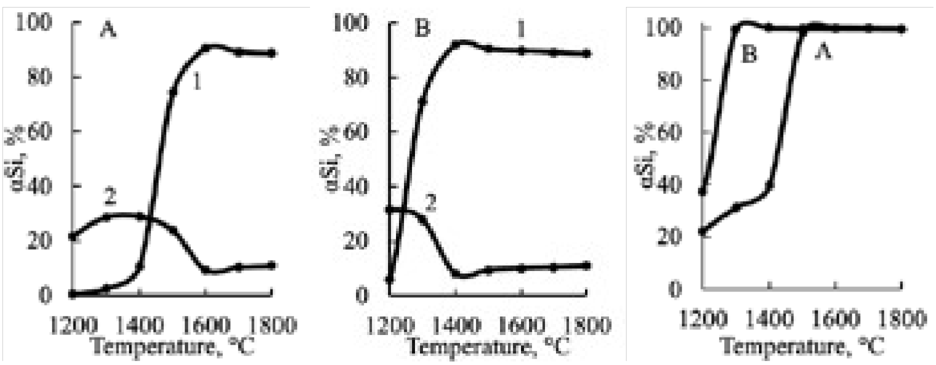
It should be noted that the optimum temperature of magnesium distillation andcalcium silicates formation depends on the pressure. So, if the pressure is reduced to 0.01 bar, then the magnesium complete distillation temperature decreases to 1600°C, and the high total transition degree ofcalcium and silicon into calcium silicates in the form of $2CaO \cdot SiO_2$ and $CaO \cdot SiO_2$ also decreases to 1300°C (figures 9, 10).



Pressure: A – 0.1 bar, B – 0.01 bar

1 – $\alpha_{Ca}(2CaO \cdot SiO_2)$, 2 – $\alpha_{Ca}(CaSiO_3)$, 3 –$\alpha_{Ca(sil)}$

Figure 9 – Effect of temperature and pressure on the equilibrium calcium extraction degree



Pressure: A – 0.1 bar, B – 0.01 bar

1 – $\alpha_{Ca}(2CaO \cdot SiO_2)$, 2 – $\alpha_{Ca}(CaSiO_3)$, 3 – $\alpha_{Ca(sil)}$

Figure 10 – Effect of temperature and pressure on the equilibrium silicon extraction degree

The practical implementation of the proposed process for obtaining magnesium and calcium silicate from the chrysotile asbestos waste can be carried out in a vacuum furnace for the continuous production of magnesium, described in (Aueshov et al., 2020: 3).

Conclusion. Based on the results obtained at the processing of the chrysotileasbestos industrial waste, the following conclusions can be drawn:

- under equilibrium conditions, in the presence of 31.8-33.9% of calcium carbide at a temperature of 1725-1883 °C and a pressure of 0.1 bar, 92-98% of magnesium is distilled off from the CAW, 80-85% of CaO is extracted into calcium silicates (mainly in $2CaO{\cdot}SiO_2$), and only 8.7-12.5% of silicon passes into the by-product – FS25 grade ferrosilicon;
- decreasing the pressure from 0.1 to 0.01 bar allows you to reduce the temperature of complete distillation of magnesium from the chrysotile-asbestos waste to 1600°C,

and the transition temperature of calcium into silicates to 1300 °C;

- the result of the electric smelting of the waste in the presence of coke and steel shavings isFS25 ferrosilicon; in this case, 74-85% of silicon and >94% of magnesium are extracted into gas and alloy, respectively.

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