Reducing Pyrometallurgical Selection of Particularly Refractory Ledge Gold Ore

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Abstract

The article is devoted to development of a brand new approach to solution of the issue related to development of efficient technologies aimed at processing of especially refractory and hard to concentrate ledge gold ore types. A new technology of such gold ore Reducing Pyrometallurgical Selection (RPS Process) utilising the direct smelting process avoiding its concentration has been developed for the purpose. Utilisation of high temperatures and liquid phase melting processes allows actually complete processing of refractory gold ores irrespective of the mostly complex resistance to processing types and with simultaneous and efficient performance of the following four process operations: a complete removal of any waste rock in the form of melted slag containing gold not exceeding 0.1–0.3 g/t; a complete transfer into the gas phase and removal of arsenic and other harmful admixtures with off gases; complete combustion of all the ore carbon containing matter types obtaining additional heat for smelting and reducing gas phase; an actually complete transfer of any precious metals into a sulphide melt, collector matte, with gold recovery of 95–99%, which yield will amount about 10% of the ledge gold ore weight. Thus, the developed technology ensures a ten-fold decrease of processed ore amounts in the process head. The RPS Process has been developed and tested in laboratories and under workshop conditions on the basis of direct electric smelting of hard to concentrate and refractory ledge gold ore from a number of deposits of Southern, Central and Eastern Kazakhstan. Such tests of the RPS Process revealed the possibility to increase throughout gold recovery by 10–15% as compared with currently achieved in dices in case of especially refractory ledge ore processing.

1. Introduction

Arrangement of highly efficient processing of complex in composition refractory and double refractory ledge gold ore types is one of fundamental but unsolved issues of the global gold producing industry. Such ore currently contains above a half of total gold resources worldwide. Hence, the majority of such ore amounts actually cannot be currently processed in the world due to lack of efficient technologies of their processing and gold and other precious metals recovery. That is the reason why the share of gold recovery from especially refractory materials is only 8–10% in the global production output.

Gold producing companies of Russia and Kazakhstan, where there are major gold carbonaceous deposits with substantial resources of gold and other precious metals, particularly need solution of the issue, as the majority of such resources are not developed nowadays [1–3]. Separate companies, which use such refractory and especially double refractory carbonaceous arsenic gold ore, show very low indicators of gold recovery and incur great metal losses with ore concentration and gold containing concentrate leaching tailings, roasted products and other products [4, 5].

The deep analysis of gold production from especially refractory primary raw material conditions in the leading countries of the world, which we have made, shows lack of prospects in commitment to existing and even considered efficient modern process flow sheets, which in many cases cannot in principle provide efficient processing of

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such ledge gold ore, with high gold and other metal recoveries. It should be noted here that the ten-fold increase of global gold production during the last 150 years has resulted in a considerable depletion of easily concentrated and gold rich ore resources, with a decrease of that metal average grades in the currently processed ledge ore (Table 1).

On the basis of the above situation and also taking into account existing natural causes of gold ore resistance and limited technological potentials of the majority of processes to recover that metal from hard to process materials, it may be unambiguously considered that brand new approaches and technologies are required to fundamentally solve the issue. In this case, taking into account the established technological in expediency of refractory and especially double refractory carbonaceous arsenic ledge gold ore concentration, such processes shall be developed and mastered first of all in relation to direct processing of gold containing materials, without their preliminary concentration.

The above provisions allow formulation of the following requirements for so-called "ideal technologies":

- a considerable reduction of ore to process volumes in the head of the process flow sheet, with complete removal of the entire waste rock volume;
- complete independence of the technology on any types of ledge gold ore resistance, the metal grade types and their phase compositions;
- complete removal of any harmful highly volatile ore components into the gas phase (As, S, Hg, etc.), with their neutralisation and complete trapping;
- complete removal of the entire ore carbonaceous matter (OCM), with its removal with the gas phase;
- concentration of the actually entire amount of gold, silver and other metals in a separate product, which yield shall be minimum;
- a demand for a metallurgical aggregate, with a high specific efficiency, space saving unit configuration and perfect catchment system, with complete neutralisation of arsenic, sulphur and other harmful charging material components.

Though development and operation of such "ideally perfect" processes of refractory gold containing material processing, which would fully comply with any of the above mentioned requirements, is most likely impossible in practice under the industrial conditions, the technologies, which are being developed on the basis of brand new approaches, shall to the maximum extent be close to such conditions to provide highly efficient and practically complete gold and other metal recovery from refractory materials.

Table 1
Gold Resources and Average Grades in Ores by Countries of the World [5, 6]

Countries	Resources, tonnes	Average Gold Grades, g/t
South Africa	18.500	2.10
USA	4.800	1.70
Canada	3.130	2.95
Indonesia	2.750	2.80
Australia	2.350	2.10
Papua New Guinea	1.740	3.20
China	1.200	3.80
Philippines	1.070	3.40

The RPS Process for refractory gold ore [7, 8] developed and tested in laboratories and under workshop conditions by scientists of the Institute Metallurgy and Ore Benefication and Eurasian Scientific and Technological Centre "Metals and Materials" (Almaty, Kazakhstan) is one of such efficient technologies to process especially refractory gold containing ledge ore.

2. Physical and Chemical Basis of the RPS Process

Physical and chemical processes related to the thermal dissociation of complex and gold containing iron and non-ferrous metal sulphide minerals, formation of matte and slag melts and transfer of all the charging material volatile components into the gas phase are the bases of the refractory ledge gold ore direct pyrometallurgical selection with gold containing matte acquisition under the RPS Process.

In addition to the above, practicability of smelting under reducing sulphideising conditions avoiding oxidation of the charging material being processed was identified on the basis of previously performed developments and tests to electrically smelt refractory gold concentrates to obtain matte on the semi-industrial and industrial scales [3].

Thus, physical and chemical interactions under the RPS Process of refractory ledge gold ore smelting conditions take place in the following sequence in the high temperature region of the process and the required reducing sulphidising potential of the gas phase in the electric furnace.

2.1. Thermal transformations of complex gold containing metal sulphides and flux materials

First of all, thermal dissociation processes of pyrite and arsenopyrite, which contain associated in them gold in “invisible” forms, take place under the reduction conditions:

$$FeS_2 = FeS + 1/2S_2\uparrow,$$

$$FeAsS = FeS + As\uparrow.$$

The main part of FeS, as an easily fusible charging material component, forms a sulphide matte phase together with other sulphides of non-ferrous metals, which matte contains a certain amount of metallic iron obtained as a result of iron oxide reduction by carbon of the refractory ore. So formed collecting matte phases have very high potentials to concentrate actually the entire gold amount in them.

2.2. Slag formation processes and the role of slag compositions in the improvement of gold recovery from the refractory material under the RPS Process conditions

A part of iron sulphide interacts with oxide compounds and may transfer to the slag melt in accordance with the following reaction:

$$3Fe_3O_4 + FeS + 5SiO_2 = 5(2FeO \cdot SiO_2) + SO_2\uparrow.$$

A thermal transformation of flux materials, with participation of the ore carbon, in particular, transformation of calcium containing fluxes, lime and gypsum, also takes place simultaneously with the thermal dissociation of complex sulphides:

$$CaCO_3 = CaO + CO_2\uparrow,$$

$$CaO + FeS + C = CaS + Fe + CO\uparrow,$$

$$CaSO_4 = CaO + SO_2\uparrow + 1/2O_2\uparrow,$$

$$CaSO_4 + 2C = CaS + 2CO_2\uparrow.$$

Further on, slag forming oxides of arsenic gold ore and flux participate in the slag melt formation:

$$2FeO \cdot SiO_2 + CaS = 2CaO \cdot SiO_2 + 2FeS.$$

The generated double components of the slag phase ($2CaO \cdot SiO_2$ and $2FeO \cdot SiO_2$), jointly with the aluminium and magnesium oxides (Al_2O_3, MgO) form the slag melt of the RPS Process.

In general, successful completion of physical, chemical and technological processes of gold containing charging material component thermal interactions, and especially that of previously unresearched and unavailable in the world practice processes of slag melt formation under the RPS Process conditions of refractory and double refractory gold ore direct smelting depends in many ways on barren minerals of waste rock or so-called slag forming oxides, which are contained in the ledge gold ore. With regard to the above and taking into account high grades of such oxides in many refractory gold ore types (about 70–95%) (Table 2), slag melt is the main product of the RPS Process; its output is within 60–80% of the charging material weight. Hence,the best charging material composition, when it consists of refractory ledge gold ore and flux, shall provide the specified values of the basic slag physical properties, i.e., viscosity, electric conductivity and flowing temperatures, which is required to achieve low gold and other metal losses with slag. In addition, achievement of slag, which would be close to that of blast furnace (~45–50% SiO_2 and 25–30% CaO), may provide its successful use in the cement producing industry and production of construction materials.

The following slag compositions are considered optimum for the RPS Process on the basis of electric smelting of gold containing refractory ledge gold ore from a number of deposits in Kazakhstan (Table 2) at a temperature of 1400–1500 °C, %: 47.5–48.9 of SiO_2, 30.1–30.9 of CaO, 4.8–7.5 of Al_2O_3, 4.0–4.7 of MgO and 2–5 of FeO. Such slag compositions correspond to their physical properties in the $CaO–SiO_2–Al_2O_3$ system at a temperature of 1500 °C: base-to-acid ratio (CaO/SiO_2) – 0.57–0.66, viscosity – 0.75–0.60 Pa · sec., electric conductivity (at 1450 °C) – 1.5–0.2 1/(Ohm · m) and fusion temperatures of 1390–1370 °C.

2.3. Processes of arsenic, sulphur and carbon complete transfer to the gas phase

The next important process operation of the RPS Process is sublimation of actually the entire amount of volatile components and complex mineral dissociation products, which have very high vapour pressure values at 1400–1500 °C.

Table 2
Chemical Compositions of Tested in 2011-2015 Refractory and Double Refractory Gold Ore and Concentrates under Laboratory Conditions by Way of the RPS Process Method in Kazakhstan

Deposit Description	Contents									
	g/t		%							
	Au	Ag	Cu	Fe	S	As	SiO_2	CaO	Al_2O_3	MgO
South Kazakhstan, Teriskey LLP Mine and Plant (2011-201)										
Zholbaristy	6.9	71.7	0.240	13.70	13.1	0.25	58.80	0.54	4.60	1.18
Shovan	7.4	330	0.290	13.89	1.5	0.22	33.90	11.80	4.90	7.70
Kelinshektau	4.8	211	0.720	23.80	25.6	0.40	24.60	5.47	<0.10	4.30
Nizhne-Kumisty	1.7	2.5	0.015	6.90	0.3	0.01	64.50	3.20	14.16	0.79
Verkhne-Kumisty	1.4-2.5	2.3-5.2	1.430	6.50	12.5	<0.01	60.40	1.57	20.34	0.60
Tailings of Thiosulphate Leaching	6.7	262	-	-	-	0.30	19.95	13.10	0.90	10.0
Central and North Kazakhstan, Mayatas LLP., Kazakhaltin JSC (2013-2015)										
Saiak-4	3.9	1.22	0.013	3.95	1.00	3.400	37.7	23.30	4.8	0.70
Mayatas	7.1	3.23	0.024	16.70	0.14	0.500	76.5	0.10	4.7	0.14
Zholimbet	2.2	3.00	0.008	8.14	1.01	0.020	55.2	4.10	12.6	4.50
Bestube	4.4	1.66	0.006	5.18	1.41	0.270	53.3	4.60	15.3	2.40
Aksu	6.5	1.08	0.050	5.92	1.41	0.012	52.4	6.04	15.7	-
East Kazakhstan, Bakirchik Mining Company (2014)										
Bakirchik (1)	5.5	0.80	-	3.45	1.45	1.00	68.2	0.95	11.5	4.03
Bakirchik (2)	12.0	1.10	-	9.50	7.90	2.05	51.6	2.20	11.2	-
Bakirchik Concentrate	44.2	1.90	0.04	10.10	7.97	5.10	36.3	1.60	13.1	1.20
Central Kazakhstan, Kazakhaltin JSC Mining and Metellurgical Company, Sayak 4 LLP Golden, Kazakhmis Smelting LLP (2009-2015)										
Saiak-4 Concentrate	50.0	46.0	0.058	13.79	6.77	16.20	24.60	12.90	3.06	-
Bestube Flotation Gold Concentrate	91.50	18.50	0.100	19.98	16.95	9.20	27.6	2.74	9.10	1.77

Thus, metallic arsenic, elementary sulphur and carbon, which interact in accordance with the following reactions in the gas phase, fly with off gases of the electric furnace:

$$6As + 4.5S_2 = 3As_2S_3,$$
$$4As + 3O_2 = 2As_2O_3,$$
$$1/2S_2 + O_2 = SO_2\uparrow,$$
(oxygen is supplied due to air suction in the dust and gas devices)
$$As_2O_3 + 3C = 2As + 3CO\uparrow.$$

In general, sulphide and oxide compounds of other non-ferrous metals, in particular, copper, lead and zinc, which are contained in initial ledge gold ore and flux, may also participate in the above mentioned physical and chemical processes during the RPS Process refractory gold ore smelting.

Under high temperature RPS Process conditions (1400–1500 °C) and on the basis of the above basic physical and chemical processes, we may consider with confidence that the ways of gold containment in the initial ore, including also various types of "invisible" sub-microscopic gold associated with sulphide minerals and ore forming carbon containing matter, are of no importance for this technology of refractory and double refractory ledge gold ore processing. Well known physical and chemical regularities of interactions in liquid phases, distributions of basic components between liquid oxide and sulphide melts and high collecting properties of matte sulphide melts as related to precious metals come into force here. Concentration of the actually entire gold amount in matte metallised melts, which are good collectors of precious metals, indicates the same.

2.4. Processes of matte and slag melt separation

Processes of matte and slag melt separation constitute the final phase of physical and chemical processes under the RPS technology of refractory gold ore processing, which to a great extent depends on the justified selection of the optimum slag composition, which has a low viscosity below 10 poise and density of about 2.52–2.12 g/cm^3 at temperatures of 1300–1380 °C. In that case, a good difference of slag and matte densities (above 2.0 g/cm^3) is achieved, which would provide the required extent of the melt separation into slag and matte taking into account densities of the obtained ferrous matte (4.44 g/cm^3 at 1300 °C).

3. RPS Process Technology

Removal of any waste rock and a part of iron as slag melt suitable for further full-scale use is the main technological process to reduce processed amounts of refractory gold ore or charging material on its basis in the process cycle head by 60–80%, as previously noted. Even if they are directed to slag disposal areas, such oxide melts are the mostly non-hazardous materials, which refer to so-called “amber” waste classes with a very low level of environmental hazards.

The special need in such pyrometallurgical selection for the majority of refractory and double refractory ledge gold ore types mined at deposits in Kazakhstan is related to very high summarised grades of non-metallic oxides in them (70–95%).

As is well known, the above mentioned high grades of waste rock oxides, first of all those of silicon earth, create the following process difficulties under conditions of classical refractory gold ore processing on the basis of the crushing – fine grinding – concentration by way of gravity and flotation – flotation concentrate roasting – roasted product cyanidation – solution electrowinning flow sheet:

- in case of fine grinding of refractory ore to a grain size of 0.074 mm, the main difficulties and high operating costs of the process stage relate to existence of hard to grind ore components, such as silicon earth and other oxide minerals;
- in case of concentration by way of gravity and flotation of ground refractory ore, above 80% of the washed ore turns into concentration tailings, which are the main source of gold losses and create certain hardships during tailings dam arrangement and servicing;
- even after concentration, flotation concentrates contain in average from 40 to 70% of the same waste rock non-metallic oxides, which again form environmentally hazardous cyanidation tailings with rather high losses of gold and other metals in them during roasted product cyanidation.

When the RPS Process is implemented, all the crushing, grinding and concentration operations are removed from the process cycle and accordingly, all the enumerated above adverse impacts of waste rock non-metallic oxides on the technology. In that case, which is the mostly important aspect, considerable gold and other metal losses with tailings are avoided.

Thus, the RPS Process provides an almost-ten-fold decrease of refractory gold ore amounts to be processed in the head of the process flow sheet, which would considerably simplify and, which is the mostly important aspect, cheapen further process operations to recover metals from the collecting matte. In addition to the above, it is recommended that such gold containing matte should be directed to the process of copper matte conversion, with gold recovery in accordance with the technologies available at copper plants. In principle, gold recovery from it may be arranged under conditions of its separate processing, in particular, under the process of its electro-membrane oxyhydrochlorination, with recovery of any components, without emission of any waste and without application of any harmful chemical agents and sodium cyanide solutions [9, 10]. Hence, the RPS Process is a highly productive, non-waste and non-cyanide technology.

Practical implementation of the developed gold containing ore processing technology includes the following: ore and flux (limestone and sulphidiser) preliminary preparation, which includes crushing to a size of -20 mm and drying to a residual moisture content of 3–6%; smelting in the electric furnace, with addition of a reducer to obtain matte, which would concentrate precious metals, dump slag and off gases with dust. Coarse dust is separated from gases by the system of coarse dust picking, which consists of a dust chamber and cyclones. Coarse dust is recycled and is routed to smelting. Gases shall be directed to fine dust picking, which takes place in wet scrubbers with lime milk and wet electric filters to neutralisesulphur dioxide and arsenic sulphide. Figure 1 describes the process flow sheet of pyrometallurgical gold containing material processing by way of the RPS Process.

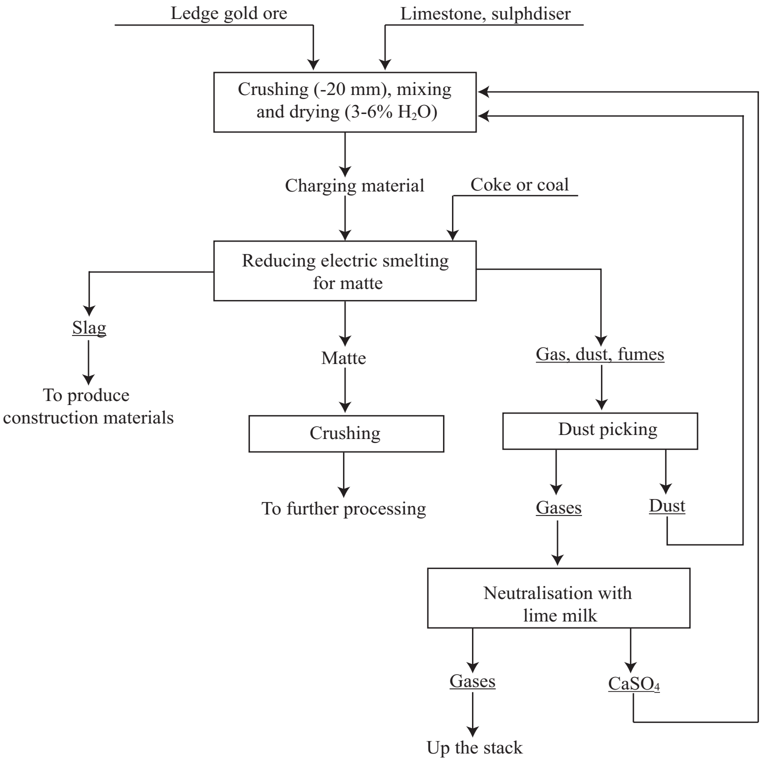

Fig. 1. Refractory Ledge Gold Ore Processing RPS Process Flow Sheet.

4. Experimental

4.1. Laboratory tests

During the last ten years, the RPS Process has been analysed in detail under laboratory conditions as related to various in chemical and mineral composition refractory and especially refractory carbonaceous and arsenicledge ore types of Kazakhstan [7, 10]. High temperature units, such as an NTS 08/16 Chamber Furnace, Nabertherm GmbH (Germany), a SNOL 12/16 ChamberElectric Resistance Furnace (Russia) and an UIP-16-10-0B Induction Smelting Unit were used as the main equipment for the RPS Process smelting of ledge gold ore. Trial smelting of gold ledge ore and concentrates were carried out within a temperature interval of 1350–1500 °C, with additional to initial ore charging of oxide and sulphide fluxes, while chamber furnaces with programmable regulation of temperature were used for weighed charges of 200–300 g, and the Induction Smelting Unit, with an infrared pyrometer to measure the furnace temperature was used for balanced smelting with weights up to 1000 g. Test smelting of charging materials were performed in alundum and graphite melting pots, which were divided after the test so that the processes of the melt separation into slag and matte could be observed (Fig. 2).

Table 2 describes chemical compositions of tested under laboratory conditions refractory ledge gold ore types from the main gold bearing regions in Kazakhstan, which differ in their chemical and phase compositions, and also in thermal properties.

Table 3 presents grades in smelting products and precious metal recoveries obtained under conditions of laboratory smelting in crucibles of gold containing charging materials, which were batched on the basis of gold ledge ore and concentrates (Table 2).

Physical and chemical properties, the structure and thermal properties of the basic products, collecting ferrous matte and slag melts were analysed in detail in the course of laboratory tests of the RPS Process. In particular, the role of calcium containing fluxes to obtain slag with optimum physical properties was analysed. Physical properties of separate slag types were determined utilising available in literature nomographic charts of values of such slag melt physical properties alteration in the CaO-SiO_2-Al_2O_3 system dependences on their basicity (CaO/SiO_2) [12]. Thus, values of the final dissolution temperature were identified within 1390–1370 °C for RPS Process slag with a basicity of 0.57–0.66, and electric conductivity for a temperature of 1450 °C value was identified within 1.5–1.2 1/(Ohm · m).

Table 4 shows the possibility to obtain slag melts with low viscosity values by adding various amounts of calcium oxide to ledge gold ore.

Table 3
Precious Metal Grades in Slag and Matte, and Gold Recovery into Collecting Matte

Initial Gold Containing Material Descriptions	Grades in Products, g/t				Gold Recovery into Matte, %
	Au		Ag		
	In Matte	In Slag	In Matte	In Slag	
Ledge Gold Ore of South Kazakhstan	15-22	0.1-0.3	63-71	3.2-5.0	95-98
Ore of Saiak-4 Deposit	34-32	<0.1	126-147	2.00-5.86	97-98
Ore of Maiatas Deposit	33-37	0.4-0.6	109-124	1.5-1.7	94-97
Ore of Zholimbet Deposit	15.0	0.008-0.24	52.0	0.73-1.70	96-98
Ore of Bestobe Deposit	15-16	0.10	50.3	0.67	98-99
Ore of Bakirchik (1) Deposit	30-33	0.10-0.16	372-373	0.69-1.38	96-98
Ore of Bakirchik (2) Deposit	47-48	<0.20	85-90	0.50	98-99
Concentrate of Saiak-4	300-360	0.25-0.60	-	-	95-97
Concentrate of Bakirchik	250-370	0.72-0.76	-	0.50-0.65	98-99
Concentrate of Bestube	302-336	0.64-0.84	49-51	1.60	99.55

Table 4
Impact of CaO on the Obtained Slag Composition and Viscosity in Case of RPS Process Smelting of Refractory Ledge Gold Ore

CaO Addition to Charging Material		Component Grades in Slag, %						Slag Viscosity, Pa · sec., at a temperature of °C		
g	%	SiO_2	CaO	MgO	Al_2O_3	FeO	CaO/SiO_2	1.400	1.450	1.500
78	15	50.2	30.8	8.1	7.0	3.9	0.60	1.5	1.0	0.8
100	20	47.2	35.0	7.7	6.5	3.6	0.74	1.0	~0.65	>0.5
125	25	44.5	38.7	7.2	6.2	3.4	0.86	1.0	>0.7	0.4

Table 5
Metal Grades in Products of RPS Process Pilot Test for Three- and Five-Component Charging Materials on the Basis of Refractory Ledge Gold Ore of Teriskey LLP Mining Company

Product Description	Contents			
	Au, g/t	Ag, g/t	Cu, %	Fe, %
Slag	<0.05-0.5	3.2-8.2	<0.01-0.07	8.01-9.97
Matte	34.5-40.0	408.0-535.2	4.0-6.2	36.90-45.68
Cyclone dust	15.64	210.2	1.4	16.12
Blister copper	516.0	1,512.86	95.0	-

4.2. Pilot tests

Pilot tests of the RPS Process electric smelting were carried out on the basis of ledge gold ores from South Kazakhstan deposits and carboniferous arsenicore of the Bakirchik Deposit in the East Kazakhstan Oblast. The first series of such pilot tests was performed at the Teriskey LLP Mining Company's Concentration Plant at an electric furnace 200 kVA in capacity in the Suzak District of the South Kazakhstan Oblast, and the second series was carried out at the test electric furnace of the Chemical and Metallurgical Institute named after Zh.N. Abishev (Karaganda, Kazakhstan).

Without going into detail about indicators and data of the above trial and pilot tests (they will be published in separate articles), Tables 5 and 6 present metal grades in matte and slag of the pilot tests of two refractory ledge gold ore types.

Table 6
Gold and Silver Grades in Slag and Matte Obtained after Trial Smelting of Charging Materials on the Basis of Refractory Ore from the Bakirchik Deposit

Product Description	Contents, g/t	
	Au	Ag
Slag	0.10-0.16	0.69-1.38
Matte	36.20-42.06	189.28-235.70

5. Results and Discussion

Experimental evidence of the RPS Process smelting laboratory tests show that the technologyis in principle able to provide efficient processing of any refractory and especially carbonaceous arsenic ledge gold ore types, which contain at least 4–5 g/t of gold. In addition to the above, it can be successfully applied to smelt unconcentrat able and ledge gold ore types, which are very complex in structure, chemical and mineral composition. The main advantage of the technology under review, its provision of charging material on the basis of refractory ledge gold ore liquid phase transformations at process temperatures of 1400–1500 °C, prevents adverse impacts of any ore resistance types, with various gold and other metal concentrations in them.

As practice of many gold producing facilities shows, presence of the various type carbon containing matter in ore causes the greatest difficulties and gold losses in the course of processing at the stages of concentration, gold concentrate roasting and ledge gold ore hydrometallurgy [13–15]. A number of plants abroad perform even a 2-staged concentrate roasting in 2 operating in series fluid-bed furnaces to transfer arsenic and carbon containing matter [4, 5]. As shown above,presence of carbon containing matter under conditions of the RPS Process smelting, on the contrary, facilitates creation of additional heat in the furnace and accordingly helps to save electric power.

The second and principally important indication of the RPS Process smelting of various in composition and resistance extent ledge gold ore types is the possibility to obtain extremely poor in precious and non-ferrous metal gradesslag melts, which are at the same time suitable to produce construction materials, which are currently in demand. In that case, a non-waste refractory ledge gold ore processing technology will be created. As Tables 5 and 6 above show, in case of mill testing of the RPS Process smelting of three- and five-component charging materials on the basis of refractory ledge ore of the Teriskey LLP Mining Company, slag contains the following: 0.05–0.50 g/t of gold, 3.2–8.2 g/t of silver and <0.01–0.07% of copper. In case of RPS Process smelting carbonaceous arsenic especially refractory ledge ore of the Bakirchik Deposit, it regularly produced slag containing 0.10–0.16 g/t of gold and 0.69–1.38 g/t of silver.

Such data testify to high degrees of precious metal recoveries into collecting matte at a level of 98–99%, as losses of the metals with slag never exceeded 1–2% of their entire amount in the charging material.

However, the following issues expectedly arise in case of actual implementation of refractory and especially carboniferous arsenic ledge gold ore types direct high temperature processing under the RPS Process: dust and gas cleaning and direct disposal of off gases from smelting units and provision of high performance indicators of great gold ore amounts direct smelting without concentration under the RPS Process. On the basis of the above issues,we, jointly with major gold producing companies and institutions of Kazakhstan, such as Kazakhaltin JSC, Kazakhmis LLP, VNIItsvetmet, and also taking into account the best world practices of especially refractory gold material processing, developed practical recommendations, technological and feasibility assessments of the process at the stages of pilot testing.

As for the issue of the RPS Process gas phase arsenic containing components trapping, neutralisation and disposal, it shall first of all take into account lessons learned during operation of industrial fluid bed furnaces at 25 major gold producing plants in foreign countries, which apply one- and two-staged processes of gold refractory ore and concentrate oxidisingroasting [4, 5]. At such companies, which process above 2000 tonnes/day of refractory carbonaceous arsenic gold ore, industrial dust and gas cleaning systems currently provide complete trapping and neutralisation of any harmful components in off gases of roasting furnaces. Designing and industrial operation of electric furnaces and other smelting units for the RPS Process shall use, and in separate cases develop, combined and highly efficient dust and gas cleaning systems consisting of a gas cooling chamber, two- and three-staged group cyclones, two-staged scrubbers for gas wet cleaning and a wet electric filter to the flue gas fan to emit treated gases into the air.

The performance and cost efficiency shall be the main indicator for the refractory gold ore direct smelting under the RPS Process technology. As Fig. 1 shows, the process flow sheet of the method provides for utilisation of electric furnaces to directly smelt refractory ore types with fluxes -20 mm in size. Here, the main part (more than a half) of operating costs falls on the power cost and consumption. Ledge ore of the southern and western Kazakhstan regions smelting mill tests steadily show that the specific electric power consumption is at a level of 450–500 kW per one tone of charging material during the RPS Process. On the basis of the industrial electric furnaces operation at copper smelters, in particular, in Zheskazgan, the cost of 1 tonne of solid charging material processing in electrothermal smelting units is nowadays US $25–30. As collecting sulphide melts (matte) constitute the basic gold containing product in the RPS Process technology, the prime cost of final commercial products (gold and other metals) also includes costs of precious metal recovery from the matte,which recovery, as shown above, will be only 10% of the amount of the charging material processed.

Taking that into account, we recommend a transfer of gold containing collecting matte to the copper matte conversion process of copper smelters and recommend recovery of gold, silver and copper in accordance with the existing technology of precious metal recovery into the blister copper electrowinning slime at the first stage of the RPS Process implementation, as the above process flow sheet shows.

Our approximate modelling for a case of smelting of 300 K t/year of refractory ore of one of the Central Kazakhstan deposits containing 7.3 g/t of gold by way of the RPS Process method in a separate electric furnace 15–20 MW in capacity and transfer of 30 K tones of collecting matte to a copper smelter showed that about 2 tonnes of that metal are possible to obtain in the electrowinning slime, with it send-to-end recovery ~91%. In that case, the economic effect as an additional annual profit after the produced gold sale will amount US $70-80 MM.

6. Conclusions

The developed and pilot tested RPS Process of especially refractory ledge gold ore types direct smelting avoiding their concentration and cyanidation stages is a new highly efficient method unavailable in the gold producing practice worldwide. The principal advantages of this technology as compared with the existing ones are to be found in the area of high gold recoveries into collecting matte (98–99%), while only 1–2% of the metal is lost with slag, which is directed to production of construction materials. Taking into account a tenfold decrease of charging material on the basis of ledge gold ore amounts in the head of the process flow sheet, it gives grounds to establish non-waste gold production on the basis of the RPS Process. In addition to the above, under the Republic of Kazakhstan conditions, the practicability of collecting gold and other metal matte melt processing at the converter process stage of one of copper smelters, with precious metal recovery under their existing technologies allows the opportunity to remove the cyanide and any other hydrometallurgical stages from the total gold production process. All the above said, and also the possibility to smelt ledge gold ore in mastered by the non-ferrous metallurgy pyrometallurgical units (an electric furnace, Vasnukov furnace) with high specific capacities as related to charging materials, ensure achievement of the stated above high performance indicators.

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