Development Strategy for Raw Materials Base of Aluminum Industry in Russia

G. G. LEPEZIN

A. A. Trofimuk United Institute of Geology, Geophysics and Mineralogy , Siberian Branch of the Russian Academy of Sciences, Pr. Akademika Koptyuga 3, Novosibirsk 630090 (Russia)

E-mail: lepezin@uiggm.nsc.ru

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Abstract

The state of affairs in aluminum industry of Russia is analyzed in detail. The problem of raw materials base is considered, and radically new solutions are suggested. The electrothermic method of aluminum production from minerals of sillimanite group without using alumina is proposed.

INTRODUCTION

Prospects for the development of virtually all segments of the world's market of aluminum for the coming years are estimated pessimistically. According to the forecast of the James King Company for 2002-2005, alumina supplies will increase by 6.7 million tons, while the demand, by 10.4 million tons. In 2005, shortage of alumina may amount to 1.9 million tons. According to the data of Barclays Capital, Prudental – Bache Int., and other expert agencies, the state of affairs in aluminum industry will be unfavourable as well. The commissioning of new facilities for aluminum production in China, India, and Norway taken into account, the competition here is expected to remain high and even to increase. In this situation, it is vitally important for Russian producers to minimize their dependence on foreign sources of raw material.

Analytical reviews [1, 22, 23, 28] devoted to the national aluminum industry emphasized that under conditions of economic depression our industry not only retained the production level of the preceding years, but also penetrated the world's market and demonstrated that it is quite competitive. Nevertheless, present welfare in this field cannot be thought of as steady or promising to be long-lived. Many smelters now in operation were constructed in the 1930–60s and need technical and technological re-equipment. These plants use powerful electrolytic cells and prebaked anodes with dry scrubbing and produce ~15 % of the total aluminum output, while in countries with developed aluminum industry, this figure is 80–100 %. Worn-out assets, low process standards, shortage of alumina, low level of domestic market consumption of the product, and high power and transport expenses are only few of all problems to be solved in the nearest future.

To raise the production profitability and reduce the production cost of aluminum, the following recommendations were given [1, 22, 23, 28, *etc.*]: 1) to create vertically and horizontally integrated structures from extraction of raw material to manufacturing of finished products from aluminum; 2) to make long-term agreements with suppliers of alumina; 3) to introduce power and resource saving technologies; 4) to build within the limits of large companies their own power-producing enterprises. These are certainly useful but too general recommendations; their realization would at best make Russian smelters approach, both organizationally and technologically, the smelters of the developed foreign countries. In the long run it would also be possible to increase the domestic consumption of aluminum. However, we still face the challenges of the source of raw materials and high transportation costs. Presently, alumina import is 3.4-3.7 million tons per year [3], the major suppliers being the post-Soviet republics Ukraine and Kazakhstan and foreign countries (Australia, Brasilia, and others).

According to expert estimates [14], Russian aluminum industry will not be competitive unless the energy costs are up to 15–17 % and transportation costs do not exceed 6–8 % of the overall cost of production. However, in reality, electric power expenses have reached 20–30 % and transportation expenses are 17–18 % (for comparison, 2–3 % in Canada). How can Siberian aluminum smelters compete with Australian smelters if they have to buy alumina in Australia and transport it by sea, and then by railroad to distances of 4000–4500 km?

The March (2003) issue of the "Vestnik RUSALa" journal referred to the information of the CRU Int. agency and considered possible behaviour of Chinese aluminum producers under conditions of further growth of electricity tariffs and alumina prices. Given $1400/ton for primary aluminum and $250/ton spot price for Al_2O_3, some companies are still capable of working with a narrow margin; but with a reduction to $1300/ton for aluminum ($1320/ton in early April, 2003) and with a price advance to $300/ton for alumina (Australian alumina price was $255/ton for the same period; the predicted price is $280-300/ton for the end of 2003 and $400/ton for 2004), many of them will become unprofitable. The situation is probably the same for Russian producers. Alumina is 30-40 % more expensive for them than, for example, for American producers. The situation is aggravated by the fact that the Government commission on protective measures in foreign trade made a decision to recommend the Government to cancel tolling schemes starting January 1, 2004. If it were not for State Duma's voting against this problem formulation, additional expenses for alumina would be inevitable. After Russia's joining the WTO and the acceptance of terms for liberalization of the power market, low-cost electric energy will vanish. Things will eventually leave cheap labour-force as the sole advantage of the Russian companies over the western competitors.

The heads of the Bratsk, Bogoslovsk, Volgograd, Volkhov, Irkutsk, Kandalaksha, Krasnoyarsk, and Sayanskiy aluminum smelters gave convincing arguments on the subject. In their letter to the Chairman of the Government of the Russian Federation ("Vostochno-Sibirskaya Pravda" of November, 3, 2001), they said that ***losses amounted to 330 USD per ton of product because of high railroad tariffs, shortage of raw material, and double taxation of aluminum and alloys export in Europe.*** Thus Russian aluminum producers speak about survival but not about their competitiveness in the world's market.

The critical state of affairs in this field is convincingly demonstrated by the history of the Cemitrade smelter (the city of Oradea, Romania) bought by the "Russian Aluminum" company. With a design output of 240 thousand tons, it produced about 15 thousand tons of alumina per month and supplied it to Russia. In 2001, because of an increase in power supply tariffs, the production cost of alumina increased by $22 per ton. Production became unprofitable and the smelter was suspended (then what was the profit they had had before the price rise?).

Crisis is largely due to recent drastic price reduction for aluminum and price rise for alumina. It hit not only Russian smelters. The Alcoa Corporation of America closed alumina plants in Brasilia, while Alcan of Canada dismissed 3.6 thousand staff members. This happened not because of raw materials shortage.

STATE OF THE RAW MATERIALS BASE OF ALUMINUM INDUSTRY IN RUSSIA

Presently we have eleven aluminum smelters in operation, including five in Siberia (in Bratsk – BrAZ, Irkutsk – IrkAZ, Krasnoyarsk – KrAZ, Sayan – SAZ, Novokuznetsk – NKAZ), two in the Urals (Bogoslovsk – BAZ, Ural – UAZ), and four in the West and Northwest of Russia (Kandalaksha – KAZ, Volkhov – VAZ, Nadvoitsk – NAZ, and Volgograd – VolAZ). Their annual output is about 3.2–3.3 million tons of aluminum, which is 15 % of the world's output. Per capita production of aluminum in

Russia (~20 kg/person) places it in the group of industrialized countries; according to per capita consumption (~1.6 kg/person), Russia is among underdeveloped countries. More than 90 % of the total amount of produced metal is shipped abroad.

Alumina is manufactured by BAZ, UAZ, VAZ, Boksitogorsk Alumina Plant, "Alumina" Corporation of Pikalevsk, and Achinsk Alumina Refinery (AAR). In 2002, their combined output of Al_2O_3 was ~2.9 million tons.

Bogoslovsk, Ural, and Boksitogorsk smelters work with bauxites, while others use nepheline ores. Production of a ton of alumina demands, on the average, from 2.5 to 7 tons of bauxites (which depends on their quality) or more than 4 tons of nepheline ores. Bauxites are concentrated in the Chelyabinsk, Sverdlovsk, Kursk, Leningrad, and Arkhangelsk regions, in the Komi Republic, and Krasnoyarsk region. They are extracted by the South-Ural and North-Ural mines, and also by the "Bauxites of Timan" mine. The latter is planning to bring the rates of extracted raw material to 1.5 million tons in 2003 and to 8 million tons thereafter. Bauxite resources in the Middle Timan deposit (Komi Republic) amount to 250 million tons.

Nephelinic syenites rank second as alumina raw materials. The Volkhov smelter and the "Alumina" Corporation of Pikalev process the ores of the Kola Peninsula; the Achinsk Alumina Refinery handles ores from the Kiya-Shaltyr deposit.

If we compare the outputs of aluminum (~3.2–3.3 million tons) and Al_2O_3 (2.9 million tons), we obtain a deficit of ~3.5–3.7 million tons of alumina, Siberian aluminum smelters being > 3.9 million tons short of alumina. The demand is partially satisfied by supplies from the Nikolaev Alumina Refinery of RUSAL holding company and partially from the Pavlodar plant, the major part of supplies being import from Australia, Brasilia, Venezuela, Guinea, India, *etc*.

Despite the lack of its own raw materials, the Sayan smelter is planning an increase of 260 thousand tons of aluminum output; a new smelter is under construction in the Irkutsk region ("Alyukom-Taishet") with a production rate of 250 thousand tons; finally, projects are being considered to construct an alumina-aluminum integrated plant using Timan bauxites in the Komi Republic (600 thousand tons) and also a supersmelter using bauxites from the North-Onega deposit (550 thousand tons). It is planned to build one to three smelters in the Leningrad Region, one in the Murmansk Region (500 thousand tons), one in the Sverdlovsk Region, and another one in the Irkutsk Region (500 thousand tons). They stake, as before, on low-cost electric energy (Leningrad, and Beloyarsk atomic power stations, Bratsk hydroelectric power station) and on long-range forecasts, predicting price rise for aluminum in view of the expected growth of aluminum consumption. Realization of construction projects will increase alumina deficit by further 1–2 million tons.

The problem of alumina deficit in Russia has been discussed for many years. Self-supplied with alumina are only smelters of SUAL holding company, producing ~25 % of aluminum manufactured in the country (~850 thousand tons per year). They have their own raw materials base. RUSAL enterprises are in a more difficult situation. Siberian bauxites are not promising as raw materials because of their poor quality and relatively minor reserves. The Chedobets deposit (Krasnoyarsk region) is among commercially promising deposits, but the best that could be done on its basis is the construction of a medium-capacity alumina plant. Other (Barzassk, Tatarsk, Boksonsk) deposits are characterized by poor quality of ores, are not sufficiently studied geologically and technologically and not readily accessible.

To supply RUSAL aluminum smelters with alumina from nephelinic syenites, at least four integrated plants comparable to the Achinsk smelter in their capacity need to be built. The ores should not be lower in quality than the ore of the Kiya-Shaltyr deposit, and the by-products (cement, soda, potash) should find application. With smelters concentrated within one region, problems of chalkstone supplies and complete slime disposal will become acute.

With a waste-free technology, one ton of alumina product should give more than 1 t of soda products and 11 t of cement. Meanwhile, the real situation here is as follows. The Achinsk alumina refinery previously produced ~4 t of cement (and now even less), and 7 t of slimes went to the dumps. It is easy to count which quantity of ecologically harmful waste accumulated after thirty three years of its being in service. With a production rate of 800−900 thousand tons of alumina per year, the waste may amount to 200 million tons or more. Optimum output of alumina is considered to be 200−250 thousand tons per year. In this case, production will be profitable, slimes will be completely disposed of, and cement will be marketed.

The main limitations of the industrial use of nephelinic syenites lie in greater material expenses and fuel, energy, and capital costs, which will dramatically increase if ores with low alumina contents (of Goryachegorsk type, Al_2O_3 ≈22 %) are used. These ores should be concentrated. This is attainable in different ways.

1. To enrich nepheline ores. This method is almost ineffective. It enables one to obtain concentrates suitable for processing by the sintering method, but affords low yields of alumina and high yields of tails.

2. To introduce bauxite additives into non-enriched nepheline ores. This will raise the alumina content in the ore mixture, decrease the coefficients of consumption according to raw materials and basic and auxiliary materials, and will raise the productivity of the alumina complex. However, the poor quality of domestic bauxites and the high iron oxide content make this way economically and technologically unacceptable.

The problem of the raw materials base seems to be resolved for Siberian RUSAL smelters. The holding company has contracted for 25 years of management of the Guinea Company "State society of Kindia bauxites." We will get the bauxites. But what shall we do with them? Siberia has no processing plants, and even if it had, transportation costs would exceed those for alumina. Thus it is anticipated that RUSAL will construct an alumina plant and subsequently a smelter in Guinea. Meanwhile, Siberian smelters will still be in need of the raw material as ever. Bratsk, Krasnoyarsk, and Sayan smelters are the greatest aluminum manufacturers in the world. Nevertheless, these giants have no future.

The natural question arises: Can we do without alumina import and thus radically change the current distribution of costs? Yes, we can. There are alternative sources of raw materials in Russia to set up on their basis large-scale production of aluminum without using alumina. Below we will try to justify our standpoint.

PROSPECTS OFFERED BY THE USE OF NEPHELINE ORES AND SILLIMANITE CONCENTRATES FOR EXPANDING ALUMINA PRODUCTION

To partially eliminate the shortage of the alumina raw material in Siberia, in 1987 the author of the present article and V. D. Semin submitted their proposals to the USSR State Planning Committee. They suggested combined processing of nepheline ores and concentrates of minerals of sillimanite group [17, 25-27]. This group includes andalusite, sillimanite, and cyanite (disthene). Their general formula is Al_2SiO_5; the composition is (wt. %): Al_2O_3 62.9, SiO_2 37.1; they occupy the fifth place (Table 1) in the aluminum content (33.3 %) next to corundum (52.9 % Al), boehmite AlOOH (45.0 % Al), diaspore AlOOH, and hydrargillite (gibbsite) $Al(OH)_3$ (34.6 % Al).

The last three minerals are bauxites − the major source of alumina. Ores containing andalusite, sillimanite, or cyanite are easily concentrated. The mass fraction of alumina among the concentrated products is 62 % (Table 2).

The suggested method of concentrating the raw material is most promising. It increases the alumina content and decreases the iron oxide content in the ore mixture. The specific consumption of raw materials and chalkstone, as well as the yield of slime, decrease. Concurrently, with a simpler phase composition of the sinters, valuable components are extracted in greater numbers, and the physicochemical properties of the fusion mixture are enhanced.

The combined processing using the sintering method enables one to create 1 : 1 mixtures of nepheline ore (NO) and cyanite-sillimanite concentrate (CSC). In this case, soda will be completely utilized, and the yield of slimes will be reduced to an optimum minimum.

The aforesaid can be illustrated by the following examples. With 30 % of cyanite-silli-

TABLE 1

Calculated demand for alumina-containing minerals, ores, concentrates, and their mixtures for the preparation of 1 t of aluminum (100 % extraction)

Mineral, rock, concentrate, mixture of products	Theoretical content of Al_2O_3, %	Theoretical content of aluminum, %	Calculated demand, t
		Minerals	
Corundum Al_2O_3	100.0	52.9	1.89
Boehmite, diaspore AlOOH		85.1	45.0 2.22
Hydrargillite (gibbsite) Al $(OH)_3$	65.4	34.6	2.89
Minerals of sillimanite group Al_2SiO_5		62.9	33.3 3.00
		Ores and concentrates	
Ores:			
bauxites	50−60	26.7−31.7	3.8−3.2
nepheline ore (NeO-1)	27.0	14.3	7.0
the same, NeO-2	22.0	11.6	8.6
Concentrates of minerals of sillimanite group (CMSG):			
CMSG-1	62.0	32.8	3.1
CMSG-2	57.0	29.7	3.3
Mixtures of nepheline ore (NeO-2) and CMSG:			
HeP = 70 %, CMSG = 30 %	32.5	17.2	HeP = 4.1 CMSG = 1.7 Σ = 5.8
HeP = 40 %, CMSG = 60 %	43.0	22.8	HeP = 1.8 CMSG = 2.6 Σ = 4.4

manite concentrate (57 mass % Al_2O_3) added to the non-enriched nepheline rock of Goryachegorsk type (22 % Al_2O_3), the mass fraction of alumina in the mixture is raised to 32.5 % (Table 3). Recall that the top quality Kola nepheline ores contain 28-29 % Al_2O_3, the ores from Kiya-Shaltyr deposit contain 27 %, the best dressing methods yield 27-30 %, the average statistical alumina content in natural nepheline is 33.15 %, and the theoretical value is 35.9 %. If a mixture contains 60 % cyanite-sillimanite concentrate and 40 % nepheline ore, Al_2O_3 will amount to 43 mass %, approximating the concentration in bauxites.

The Kiya-Shaltyr deposit is worked out selectively; *i. e.*, the richest ores are taken out, while the ordinary ones go to the dump. The cyanite-sillimanite concentrate additions will make it possible to stabilise the alumina content at a level required by technology. Continuous mining will prolong the life of the Achinsk alumina refinery. This will reduce the specific consumption of chalkstone and the yield of slimes, and, at the cost of this reduction, materials and power consumption of the process will drop, while the economic factors and the ecological situation will improve. Laboratory investigations into combined processing of CSC and NO, which made it possible to draw the above conclusions, were conducted with the use of Kiya-Shaltyr urtites, Goryachegorsk theralites, and Bazybay sillimanite concentrates [25−27].

Practical implementation of these suggestions would make it possible:

1) to raise the productivity (for example, at AAR) and alumina output using current facilities and technology by a factor of 1.2−1.6 if an ore mixture with 30−60 % cyanite-sillimanite concentrate is employed;

TABLE 2

Chemical analyses of sillimanites, their concentrates, nephelines, and nephelinic syenites, %

SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
Theoretical formulation of sillimanites – Al_2SiO_5								
37.1	–	62.9	–	–	–	–	–	–
Average formulation of sillimanites from Russian deposits (n = 186)								
37.01	–	62.72	0.29	0.01	0.03	0.01	0.00	0.00
Selective chemical analyses of sillimanite concentrates from Russian deposits								
40.06	0.55	57.07	0.61	0.10	0.01	0.06	0.40	0.06
39.01	0.25	59.47	0.10	0.00	0.03	0.03	0.22	0.10
37.47	0.67	60.45	0.37	0.10	0.00	0.03	0.09	0.05
36.78	0.35	62.64	0.00	0.10	0.00	0.03	0.00	0.06
37.21	0.23	60.20	0.26	0.10	0.09	0.54	0.00	0.53
37.57	0.66	60.40	0.49	0.10	0.05	0.06	0.00	0.30
Theoretical composition of nepheline – $NaAlSiO_4$								
42.30	–	35.89	–	–	–	–	21.81	–
Average composition of natural nepheline (n = 182)								
42.00	–	33.21	1.17	–	0.11	–	14.65	7.07
Nepheline ores of the Kiya-Shaltyr deposit								
40.30	–	27.00	4.40	–	–	7.90	14.00	
Goryachegorsk ores								
43.00	–	22.00	9.30	–	–	7.00	10.00	

TABLE 3

Chemical composition of nepheline ores, cyanite concentrates, and ore mixtures, %

Ore or ore mixture	Chemical composition of ore or ore mixture				
	SiO_2	Al_2O_3	Fe_2O_3	CaO	$Na_2O + K_2O$
Kiya-Shaltyr nepheline ore – Kn	40.30	27.00	4.40	7.90	14.00
Goryachyegorsk nepheline ore – Gn	43.00	22.00	9.30	7.00	10.00
Cyanite concentrate – C	40.06	57.07	0.61	0.06	0.46
Kiya-Shaltyr nepheline ore + cyanite concentrate (Kn + C)					
0.7Kn + 0.3C	40.23	36.02	3.26	5.55	9.94
0.4Kn + 0.6C	40.16	45.04	2.13	3.20	5.88
Goryachegorsk nepheline ore + cyanite concentrate (Gn + C)					
0.7Kn + 0.3C	42.12	32.52	6.69	4.92	7.14
0.4Kn + 0.6C	41.24	43.04	4.09	2.84	4.28

2) to reduce the specific capital costs for expanding the available alumina plants and constructing new ones;

3) to reduce the yield of slimes and the maintenance cost of the production of one ton of alumina, as well as power and materials capacity and labour costs;

4) to use low quality nepheline ores without dressing.

As combined processing technology of nepheline ores and sillimanite concentrates was developed under laboratory conditions [25–27], a pilot test is needed to check its effectiveness.

PROSPECTS FOR SETTING UP COMMERCIAL PRODUCTION OF SILUMIN AND ALUMINUM BASED ON SILLIMANITES USING ELECTROTHERMICS

The problem in question may be treated in a more radical way. The electrothermic method of silumin and aluminum production has not yet been discussed in the literature.

Silumin is an alloy of silicon and aluminum, which has low density (2.4–2.7 g/cm^3), high specific strength at ambient temperature, and good foundry properties. The mass fraction of silicon can vary from 4.5–6.0 to 20–22 % in samples of different grades. Incorporation of minor quantities of elements such as Mn, Ni, Ti, Cu, Mg, *etc*. modifies the physical characteristics of the alloys, which makes them applicable to various industries.

Silumins have found application in manufacturing armoured protection for combat equipment (for example, "Marder" infantry fighting vehicle in Germany has a cast silumin case), in casting the accessories of powerful aviation engines, internal combustion engines, carburettor cases, cylinder heads, fuel element cans of atomic power stations (USA, Norway, Canada, UK), *etc.* More than half of all foundry non-ferrous alloys employed in aviation engineering and transport engineering are manufactured from silumin.

Silumin is currently obtained by fusion of crystalline silicon and aluminum in electric or combustion furnaces. This procedure requires electrolytic production of aluminum and is characterized by high production expenses for alumina, anodic stuff, cryolite, aluminum fluoride, electric energy, and also by high investments into construction of large departments with electrolytic cells and converting stations.

Electrothermics is an alternative to the technology discussed above*.

Direct ore-smelting treatment of high-alumina minerals (kaolin, andalusite, sillimanite, and cyanite) in powerful electric furnaces produces an alloy with 32–35 % Si as an intermediate, which is remelted to the standard quality silumin and aluminum during subsequent metallurgical treatment.

Electrothermic aluminum was first obtained in the form of an alloy in the 1880s in the USA.

The ore-smelting procedure was actively developed in the 1930s in Switzerland, France, and Germany [2, 9, 10]. Kaolin was used for primary alloy smelting, and lump charcoal with pitch coke was employed as a reducing agent. The electrothermic method was developed to the pilot plant level. The situation progressed to the point of commercial production (Metallgesellschaft Company, Germany, 1926).

Investigations in this field were actively developed in this country. A two-stage process for treatment of the silicon-aluminum raw material [8] has been devised in VAMI (Russian National Aluminum and Magnesium Institute) under laboratory and large scale experimental conditions. At the first stage of the process, electrothermic ore-reduction melting of the raw material is conducted; at the second stage, the electrothermic alloy undergoes reprocessing to form aluminum master alloys or commercial-grade aluminum. The scheme was implemented on an industrial scale at the Dnieper (since 1990, Zaporozhye) smelter in 1964. The smelting of an aluminum-silicon alloy occurs here by reductive smelting of briquettes of cyanite-sillimanite concentrate, kaolin, alumina, and reducing agents. Mixtures of lump charcoal, petroleum coke, mineral coal, and wood ash were used as reducing agents.

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*After this paper had been submitted for publication in the "Chemistry for Sustainable Development," an article "Electrothermic Production of Aluminum-Silicon Alloys: Start and Development" by A. M. Saltykov and A. Yu. Baimakov appeared (*Tsvet. Metally*, 7 (2003) 101). It considered details of this problem and gave numerous examples of practical application of electrothermics.

According to numerous expert estimates, electrothermic production of silumin and aluminum has the following advantages [2, 4–14].

1. The complicated and expensive production of alumina, which is essential to the electrolytic preparation of aluminum, can be eliminated from the production cycle.

2. The capacity of an ore heat-treating furnace is much higher than the capacity of an electrolyzer. For example, a single furnace with an annual output of 10 thousand tons of aluminum can replace 30 electrolyzers.

3. There is no need for alternating to direct current conversion, which reduces electric power losses.

4. No need to use fluorides.

5. From sillimanites, silico-aluminum is manufactured by using rather cheap and readily available reducing agents.

6. Electric power consumption per product unit may decrease to 20 %; and the production cost, to 30 %.

7. Constructing a plant with an ore heat-treating furnace demands 30–40 % less capital outlays than the construction of alumina and electrolytic departments.

Table 4 compares the technical and economic indices of different methods for producing aluminum and its alloys [15]. Evidently, silumin production is highly profitable even with the use of electrolytic aluminum for dilution.

There are two more points that deserve our attention. The raw material being local, the dependence on the external raw materials is completely eliminated, and transportation costs are minimized. The electrothermic method reduces the specific and capital costs. This directly depends on the unit capacity of the ore heat-treating furnace. The capacity may be increased by plasma heating, which enables one:

– to attain high temperatures for high concentrations of energy in the reaction chamber;

– to stabilize the electric operating conditions of the furnace, these being independent of the electric properties of the fusion mixture;

– to induce high voltage on the plasma arc, which allows one to use more powerful plasma generators for moderate current intensity;

– to work within a wide temperature range in any medium. Argon, hydrogen, air, natural gas, and their mixtures can be used as plasma generating agents.

According to the available publications, if a plasma generator is used in a melting unit, the estimated energy consumption will be 10–12 thousand kW h/t of an aluminum-silicon alloy.

A demonstrative example is also provided by a comparative analysis of production costs for the preparation of silumin with 85 % Al and 15 % Si by fusion of electrolytic aluminum and crystalline silicon, and by the electrothermic method using a mixture of cyanite (the least expensive of all sillimanite minerals) and technical alumina. The world prices for the components are (US dollars per ton): aluminum 1400, crystalline silicon 1200, alumina 300, cyanite concentrate 165.

The first version: $1400/ton × 0.85 + $1200/ton × 0.15 = $1370/ton

In the second version, 0.866 t of cyanite (theoretical content, %: Al 33.30, Si 17.33) and 1.061 ton of alumina (theoretical Al content is 52.92 %) is required to produce one ton of

TABLE 4

Technical and economical characteristics of the electrothermic method for the production of aluminum and its alloys compared to the electrolytic method

Characteristic per 1 ton of product	Foundry aluminum alloys	Wrought alloys and aluminum	Silumin obtained by dilution
Reduction of capital investments, %	30–40	30–35	10–12
Reduction of production price, %	25–35	15–25	8–10
Reduction of electric power consumption, %	10–15	10–15	5–7
Increase in labour productivity, %	20–40		10

silumin of the same composition. The cost of the raw material is

$$\$165/t \times 0.866\ t + \$300/t \times 1.061\ t$$
$$= \$142.88 + \$318.30 = \$461.2$$

The second version neglected possible expenses on kaolin (~\$30–35/t) and reducing agents. In addition, the aluminum content in the cyanite concentrate will actually be 2–3 % less than the theoretical content in cyanite. However, all of this put together cannot tangibly affect the proportion of expenses. The expenses are substantially higher in the first version.

RAW MATERIALS BASE FOR ELECTROTHERMIC PRODUCTION OF SILUMIN AND ALUMINUM

The electrothermic process for the production of silumin and aluminum from sillimanites is quite developed, efficient, economically justified, and has been tested on an industrial scale. Then why don't we bring it in operation in this country? Do we really lack raw materials of this kind? On the contrary, the resources amount to billions of tons (Table 5). The largest deposits are concentrated in four provinces [18, 20, 21].

Keivsk group of deposits (New Shuururta, Tyapsh-Manyuk, Chervurta, *etc.*), Kola Peninsula. Cyanite ore reserves amount to 3.4 billion tons; prospective resources, to 11 billion tons. According to the reports of expert organizations, an ore mining and processing enterprise with an annual output of cyanite concentrate of up to 7.5 million tons can be built based on the New Shuururta deposit alone. With 57 mass % Al_2O_3 in the concentrate (first grade), the total quantity of aluminum will be 2.26 million tons; *i. e.*, approximately the current annual output of smelters from the "Russian aluminum" holding company.

Deposits and ore manifestations in Sverdlovsk and Chelyabinsk regions [20, 21]. Malo-Brusyansk, Abramovka, Sosnovsk, Kosulinsk, Karabash, Malo-Kasli, Borisov, Mikhaylovsk, and other deposits are located in regions with a developed infrastructure, not far from railways. The total reserves based on cyanite amount to 20-25 million tons.

Nearly all of these deposits can be excavated. The ores are easy to dress. The alumina content in the concentrates is up to 62 %; iron microimpurities were detected in insignificant amounts (see Table 2).

The explored reserves of sillimanites in this country are over 400 million tons based on the end product (aluminum). If the output of aluminum equals the current output of 3.3 million tons per year, the ores will last for more than 120 years.

Sillimanite-bearing ores are not mined in Russia, although this country is the world's

TABLE 5

Known reserves and prospective resources of ores, sillimanites (Al_2SiO_5), alumina, and aluminum in Russia, thousand tons

Region	Ore	Al_2SiO_5	Al_2O_3	Al
Known reserves (C_2, C_1, A, B classes)				
Kola Pen.	3 400 000	1 186 879	676 518	358 556
Karelia	116 820	25 000	14 250	7553
Ural Mountains	66 684	11 710	6675	3537
Siberia	511 750	13 109	74 732	39 608
Total	4 095 254	1 236 698	772 175	409 254
Prospective resources (P_2, P_3 classes)				
Kola Pen.	11 000 000	3 840 000	2 188 230	1 159 762
Ural Mountains	109 890	30 000	17 100	9063
Siberia	8 138 400	2 588 517	1 475 455	781 991
Total	19 248 290	6 458 517	3 680 785	1 950 816

leader in their resources. With a reasonable approach to mining, the deposits would suffice for large-scale production of not only alumina, silumin, and aluminum, but also of high-alumina refractories, ceramics, and other products. It is essential that a particular deposit be estimated from the viewpoint of its real potential.

It is clear that large-scale electrothermic production of aluminum cannot be set up quickly in Russia. Therefore, the following proposals provide for gradual transition from one kind of raw material to another, and from one technology to another.

1. At the first stage, it is recommended to develop a sillimanite deposit with an output of the concentrate of 10-30 thousand tons per year. The deposit should be located in a region with a developed infrastructure, not far from the railway. Deposits of this kind are available in Russia; their development will take one or two years, and rather small capital costs will be required. This is a safe project, since the products are in demand in heat-resistant, ceramic, and other industries of national economy. With the concentrates obtained, various kinds of laboratory and pilot tests can be conducted.

2. To carry out pilot trials to test combined treatment of nepheline ores and cyanite-sillimanite concentrates. Previous experiments were conducted under laboratory conditions and yielded good results. If they are reproduced on an industrial scale, the alumina output (for example, at the Achinsk Alumina Refinery) can be raised by a factor of 1.3-1.6 using current facilities and current technology and a mixture of 70−40 % (22 % Al_2O_3) low-quality ore of Goryachegorsk type and 30−60 % (57 % Al_2O_3) cyanite-sillimanite concentrate. This will make it possible to substantially reduce the import of the raw material.

3. Laboratory experiments and then pilot trials are to be conducted using modern developments to test electrothermic production of silicon-aluminum alloys from sillimanite concentrates. Silumin production using this method will make it possible to save electrolytic aluminum and deficient alumina.

4. The next step is a gradual transition to the development of large sillimanite deposits and setup of electrothermic production of silumin and industrial production of aluminum on this basis.

5. To stop building aluminum smelters using foreign raw material. Their product cannot be competitive, primarily, because of high transportation costs. How can we get rid of 330 USD losses per ton of aluminum and its alloys mentioned by the heads of smelters, who addressed the Chairman of the Government of the Russian Federation? The single way out is to have our own, rather low-priced raw material and an economically sound technology of its processing.

What we suggest is not redecoration of aluminum industry, but a radically new solution to the problem of the raw materials base. Our country is not rich in bauxites, but it is fortunate in having sillimanite deposits, so it would be extremely unreasonable to miss this opportunity.

The author of the present contribution is a geologist who worked at practically all deposits of the former USSR; he has all information on alumina raw materials and thinks that the future of Russian aluminum lies in the minerals of the sillimanite group.

As mentioned above, construction projects are now being discussed to set up new aluminum smelters. Why shall we do this in a situation when the existing smelters are not supplied with alumina and rely on import? If we have an excess of low-cost electric energy, then why don't we return to electrothermic production of silumin and aluminum from sillimanites and why don't we build a plant (or plants) for their treatment? The electrothermic process has been developed and put into operation (Zaporozhye smelter); it has good economic characteristics. Resources of this kind of raw material total billions of tons. There are several discovered deposits ready to be mined (Keyvsk group, Khizovara, Kitoy, Kyakhta, Tymbinsk, *etc.*); they can be excavated, and the resulting concentrates are of high quality.

The question arises: Why did not electrothermics receive wide recognition abroad? Successful investigations in this field were conducted in the 1930s in Germany, France, Switzerland, and other countries.

The answer is simple. First, sillimanite resources are limited in these countries. They total ~450 million tons in the major mining countries (Republic of South Africa, USA, India, and France), while in this country, explored reserves from the Keivsk group of deposits (Kola Peninsula) alone exceed 3.4 billion tons. Second, Australia, Brasilia, and other countries possess high-quality bauxites not available in Russia, so why should they be involved in this problem at the present stage?

OTHER POTENTIAL APPLICATIONS OF SILLIMANITES

Sillimanite raw materials may be used not only in the production of alumina, silumin, and aluminum, but also in many other fields [16, 19]. The minerals are anhydrous; they possess good fireproof properties and high melting points. They are stable against deformations. They do not soften upon heating and are not liable to chemical corrosion and abrasion. The refractories prepared from them have found application in iron and steel industry, glass production, building of coke ovens, open-hearth and glass furnaces, ceramic and induction furnaces, and cement roasting furnaces; they are also useful for lining glass-pouring ladle pots, for blockwork of cupola furnaces, boiler furnaces, and flue ducts, and for manufacturing details of rocket engines and devices for high-temperature processes. Ceramics, glazes, enamels, special glasses, high-tension porcelain, non-slippery floor tile, friction material for brake blocks, and various kinds of casting molds are made on the basis of these minerals. In addition, sillimanite showed good catalytic qualities in treatment of oil products.

High-alumina refractories are raw materials No. 1 for metallurgical plants of developed countries. This group is subdivided into mullite-silica, mullite, and mullite-corundum materials with refractory quality of 1750–1850, 1800–1900, and 1850–1950 °C.

At smelters of the USA, Western Europe, and Japan, these materials are used in converter and electric arc processes and in continuous steel casting machines (blocks for blockwork, large-block structures, fibrous materials, sand-cement and plastic masses), for preparing louver gates of teeming ladles (50 % of continuous-casting blocks are manufactured on equipment of this kind in Japan); for lining ladle pots (for example, sand-cement high-alumina ramming of "Thyssen" ladle pots), dipped nozzles, *etc*.

An important application is high refractory porous ceramics (super-duty lightweights): various heat insulators used for lining boiler furnaces on tankers, hot blowers in blast furnaces, interlayer in glass furnaces, setups for off-furnace liquid steel degassing.

Other types of product are white refractories, rods of welding apparatuses, fibrous ceramic and flexible insulating coatings, equipment for roasting furnaces, catalysts, molten shells, fibres, honeycombs, and protective coatings.

The major producers of andalusite, sillimanite, and cyanite abroad are the Republic of South Africa, USA, India, France, Sweden, Spain, and Ukraine, where the total output of the product is 700–750 thousand tons per year.

The concentrates are in demand on the world market. The prices for them are (USD per ton, 2000): cyanite 140–170, calcined cyanite 250–280, andalusite 172–184, sillimanite 220–320.

From the aforesaid one can conclude that sillimanites have many applications; there is enormous demand (according to the former Soyuzogneupor, St. Petersburg Institute of Refractories (VIO), and East Research and Project Institute of the High-Heat Industry (VOSTIO), the demand is 300–400 thousand tons per year for high-heat industry alone); therefore, opening of sillimanite deposits is a safe project.

TECHNICAL AND ECONOMIC BACKGROUND FOR OPENING SILLIMANITE DEPOSITS

Deposits abroad are developed by excavation when the content of the useful component in the ores is more than 10 % and their reserves are over one million ton. The dressing methods are gravitation, flotation, and electromagnetic and electric separation. The output of the processing plants is 5, 10, 30, and seldom more than 50 thousand tons of concentrates per year. The characteristics of the commercial product (content, mass %): superior quality – Al_2O_3 > 57.0; TiO_2 < 0.6; Fe_2O_3 < 0.5; $Na_2O + K_2O$ < 1.0; first grade – Al_2O_3 56.0, TiO_2 0.8, Fe_2O_3 0.6, $Na_2O + K_2O$ 1.2; second grade – Al_2O_3 54.0, TiO_2 1.2, Fe_2O_3 0.8, $Na_2O + K_2O$ 1.5; third grade – Al_2O_3 44.0, TiO_2 2.0, Fe_2O_3 1.2, $Na_2O + K_2O$ 1.6. The sizes of fractions (mesh): 35, 40, 100, 200, 325.

Ore and sillimanites have been extracted since 1914. It was at that time that the spark plugs for aircraft engines started to be manufactured from cyanite. Broad experience on mining and concentrate production has accumulated in the world (Republic of South Africa, USA, India, France, Ukraine, *etc.*), so there will be no difficulties with engineering solutions.

It remains to estimate the economic aspect of the project. Since no deposits of this type are being developed and no specialized dressing plants exist in this country, the problem will be treated by comparing the production of this and other kinds of raw materials. Two examples are considered below.

Example 1. The "Black Hill" deposit of sillimanites (Buryatia) was discovered in 1955 and explored in 1956–1959. It lies 20 km from the railway (Khoronkhoy railway station), near the navigable Selenga river and Ulan Ude – Kyakhta highway. The ores here have an extremely simple mineralogical composition and are suitable for non-waste processing (sillimanite for alumina, silumin, aluminum, refractories, ceramics, *etc.*; quartz for glass-making). The reserves of the raw material amount to 4.1 million tons.

A dressing plant is in operation in the town of Khoronkhoy 15 km away from the "Black Hill." It was specially constructed for processing sillimanite quartzites and had produced fluorite concentrate from Mongolian ores until 1993. The amount of the processed raw material was ~150 thousand tons per year, and the output was ~35 thousand tons of metallurgical fluorspar, whose world price is $65/ton. If sold on the world market, fluorite will yield

$65/t × 35 thousand tons = $2.3 million

Suppose the plant switches over to the production of sillimanite, quartz, and rutile (for which it was constructed). With the same rate of ore processing (based on 70 % extraction) we will obtain the following quantity of the sillimanite concentrate (its mean mass fraction in the ores is ≈ 33 %):

150 thousand tons × 0.33 × 0.7 = 35 thousand tons

The revenue from its sale (with a minimum world price of $220/ton) will be

35 thousand tons × $220/t = $7.7 million

If the potential revenue from the sale of quartz ($30/t) and rutile ($540/t) is added to this, we obtain

Quartz ($\bar{X}$ = 63 %):
150 thousand tons × 0.63 × 0.7 × $30/t = $2 million

Rutile ($\bar{X}$ = 1.1 %):
150 thousand tons × 0.011 × 0.7 × $540/t = $620 thousand

The total revenue will be

$7.7 million + $2.0 million + $0.62 million = $10.3 million

Obviously, the comparison is not in favour of fluorite. The results will be even more illustrative if we compare net profits, but not the overall revenue. With more or less comparable specific production costs of concentrates (the dressing schemes include the same operations: granulating, fine crushing, flotation, drying, *etc.*), it is not necessary to buy sillimanite ores (the deposit is nearby) and to pay customs duties. In addition, fluorite goes for sale, whereas the products obtained from Kyakhta ores can serve to set up productions of alumina, silumin, aluminum, ceramic, glass, refractory and other materials.

Example 2. The Bazybai deposit of sillimanite quartzites in the Krasnoyarsk region is comparable to the Kyakhta deposit in mineralogical composition (mass %): Sil 25, Qua 65, Rut 0.7. Prospective reserves of ores total ($P_2 + P_3$ classes) 412.4 million tons or (recalculated) sillimanite 103.1, quartz 268, rutile 2.9 million tons. The theoretical composition of sillimanite (%): Al_2O_3 62.9, SiO_2 37.1; Al 33.3, Si 17.3.

The resources of alumina, aluminum, and silicon (based on sillimanite) are

alumina: 103.1 million tons × 0.629
= 64.8 million tons

aluminum: 103.1 million tons × 0.33
= 34.3 million tons

silicon: 103.1 million tons × 0.173
= 17.8 million tons

The “Olimpiadinsk” gold-bearing deposit (Krasnoyarsk region) is mined by the “Polyus” prospecting company. In 2002, this company planned to mine 6 million tons of ores and to extract 30 t of gold, but the real extract was 25.5 t.

If all of this gold is sold on the world market, the revenue will be

$10/g × 25.5 t = $255 million

Comparative analysis. Suppose the development of the Bazybay deposit will give the same quantity of mined rock as the mining of the gold-bearing deposit. Different variants of subsequent production and sale are conceivable.

The compositions of the products that may be involved in the project (mass %): sillimanite Al 33.3; Si 17.3; silumin Al 85, Si 15; alumina Al 52.9. The world prices are (USD per ton): sillimanite 220, alumina 300, aluminum 1400, silumin 1600. The extraction percent is taken to be 70 % in all cases.

Variant 1. Sillimanite, quartz, and rutile are extracted and then sold at world prices. The expected production rates are

Sil: 6.0 million tons × 0.25 × 0.7
= 1.05 million tons

Qua: 6.0 million tons × 0.65 × 0.7
= 2.7 million tons

Rut: 6.0 million tons × 0.007 − 0.7
= 29.4 thousand tons

The revenues from sales are

Sil: 1.05 million tons × $220/t = $231 million

Qua: 2.7 million tons × $30/t = $81 million

Rut: 29.4 thousand tons × $540/t = $15.9 million

Total − $327.7 million

Variant 2. Aluminum and silicon are extracted from the obtained sillimanite. Their possible production rates are

Al: 1.05 million tons × 0.333 × 0.7
= 245 thousand tons

Si: 1.05 million tons × 0.173 × 0.7
= 127 thousand tons

The revenues from sales are

Al: $1400/t × 245 thousand tons = $343 million

Si: $1200/t × 127 thousand tons = $152.4 million

Total − $495.4 million

With added revenues from sales of quartz and rutile we have

$495.4 million + $81 million + $15.9 million
= $592.3 million

TABLE 6

Production rates of sillimanite, quartz, rutile, silumin, aluminum, and silicon, million tons

Product	Extraction, %			
	70	80	90	100
		Variant I		
Sillimanite	1.05	1.20	1.35	1.50
Quartz		2.7	3.1	3.5 3.9
Rutile	0.0294	0.0336	0.0378	0.0420
		Variant II		
Aluminum	0.245	0.320	0.405	0.500
Silicon	0.127	0.166	0.210	0.260
		Variant III		
Silumin	1.211	1.384	1.557	1.730
Demand for aluminum	0.6797	0.7764	0.8739	0.9710

TABLE 7

Dependence of the total revenues on the extraction percent, million dollars

Extraction, %	Variants		
	I	II	III
70	327.9	591.9	495.3
80	374.7	757.7	794.7
90	421.6	943.6	1392
100	468	1150.4	1547

Variant 3. Sillimanite goes for production of silumin of the same composition, the excess of silicon being scavenged by aluminum. The potential quantity of the silumin product is 1.05 million tons × 0.173 : 0.15 = 1.211 million tons.

An aluminum addition is required.

Sillimanite: 1.05 million tons × 0.333 = 349.7 thousand tons
(1.211 million tons × 0.85) − 349.7 thousand tons = 679.7 thousand tons

The revenues from silumin sales are

$1600/t × 1.211 million tons = $1.938 billion × 0.7 = $1.356 billion

Expenses on aluminum:

679.7 thousand tons × $1400/t = $951.6 million

The revenues minus expenses for aluminum:

$1.356 billion − $951.6 million = $398.4 million

The same figure, but including the revenues from quartz and rutile sales:

$398.4 million + $81 million + $15.9 million = $495.3 million

In the example above, the costs for silumin production can be significantly reduced if local aluminum or, even better, scrap metal is used for dilution.

Thus we have considered variants of industrial productions set up on the basis of sillimanite quartzites of the Bazybay deposit. Variant 1 involves processing of equivalent quantities of mined rock, and suggests that the revenues from the sales of sillimanite, quartz, and rutile will exceed those from gold sales by more than $70 million. In this case, the output will depend strongly on the degree of extraction (Table 6).

The increased degree of extraction will result in growth of profits, which amount to dozens and hundreds of millions of dollars (Table 7). It is reasonable to constantly improve the production process because this ultimately is the critical factor.

The data obtained above can also be compared with the results of aluminum production. Let us take the Sayan smelter as an analogue with modern equipment. Its annual output is ~400 thousand tons of aluminum. The possible revenue from sales is 400 thousand tons x $1400/ton = $560 million. Subtraction of expenses for alumina from this gives $560 million − (400 thousand tons : 0.529 × $300/t) = $330 million. Again any variant of those considered above looks preferable.

Based on gold mined by "Polyus", one can at best construct a refinery and a jeweller factory, while on the basis of sillimanite and quartz one can build an aluminum smelter, refractory and ceramic plants, glass plant, and others. A profound economic and technical analysis will reveal what particular productions should be set up and in which sequence.

CONCLUSIONS

A detailed analysis of the state of affairs in national aluminum industry makes it possible to draw a number of important conclusions.

1. With current rates of aluminum production (especially in Siberia), the existing problem of alumina shortage in Russia cannot be solved by using local raw materials (bauxites, nepheline ores, synnyrites) because of their low quality and relatively small reserves.

2. Operation of aluminum smelters with import alumina also holds no promise. Purchase

and transportation costs can be compensated, if at all, only by cheap labour and low-cost electric energy.

3. The problem of alumina shortage can be partially solved by co-processing of mixtures of nepheline ores and sillimanite concentrates.

4. We must reject the traditional methods of aluminum production. The future may lie with sillimanites. The change-over to the new kind of raw material will be difficult and lengthy, but we have no other way out.

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