RESULTS OF THE ELECTROCHEMICAL TREATMENT OF HYDROTHERMAL SEPARATE AT THE MUTNOVSKOE HYDROTHERMAL FIELD (KAMCHATKA, RUSSIA)

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ABSTRACT

We have studied silica precipitation from the hydrothermal solution by electrochemical coagulation method in the laboratory and Mutnovskoe field conditions. Coagulant was added to the solution from the dissoluble metal electrodes (steel, copper, aluminium) under passing direct electric current. We found treatment with aluminium electrodes to be the most effective. In these experiments silica and aluminium concentration in solution, solution pH were determined and electrodes voltage was recorded. Settling rates of the coagulated silica flakes and the time of solution clarification were also measured. Current strength, solution temperature and distance between the electrodes plates were changed in experiments. The theoretical functions expressing the dependence of silica concentration in solution on treatment duration and the quantity of electric energy consumed during the treatment were found. The rate of aluminium electrodes dissolving and amount of coagulant used for treatment were calculated. With the help of X-Ray analysis it was obtained the amorphous structure of material precipitated by the electric treatment. On the base of the experimental data we evaluated the parameters of pilot electrocoagulator necessary for treatment of 1 kg/s of hydrothermal separate flow.

INTRODUCTION

One of the important problems restricting the scale of geothermal resources usage is formation of solid deposits in wells and heat equipment (Thomas D.M., Gudmundsson J.S., 1989). In most cases amorphous dioxide of silicium SiO₂ (silica) forms the main part of deposits.

The purpose of silica extraction from the hydrothermal separate is to reduce the rate of the solid deposits growth in reinjection wells. Besides it, silica extraction will give the opportunity for complex using of geothermal resources (Harper R.T., Thain I.A., Johnston J.H., 1992, 1995): a). generation of additional electric energy (10-20%) and heat recovery as a result of reinjection temperature reducing; b). obtaining an amorphous silica SiO₂ as a by-product; c). stable removal more valuable minerals (Li, B, As) during next stages of chemical treatment.

The experience in development of geothermal silica extraction and utilization technology has been accumulated in New Zealand, Mexico and Iceland. In New Zealand and in Mexico the scheme of silica extraction with adding of lime as a coagulant was developed: 20-40 mg/kg of CaO in Cerro-Prieto (Hurtado R., Mercado S., Gamino H.,1989) and up to 400 mg/kg of CaO in Wairakei and 700 mg/kg in Broadlands (Rothbaum H.P., Anderton B.H.,1975). The scheme included the stages of solution ageing before of lime adding and separation of precipitated silica in clarifier (Weres O., Tsao L.,1981). In Iceland was proposed another approach. This approach suggested the solution pre-evaporation and the recirculation of silica slurry coagulant treated in an electromagnetic field (Gudmundsson S.R., Einarsson E.,1989).

The aim of our work was to research the possibility of using the coagulant added to the solution from the dissoluble metal electrodes under passing direct electric current. Ability of such coagulant to precipitate silica was usually higher than of dispersed coagulant added to the solution by stirring. Electrochemical treatment allowed to reduce silica concentration in hydrothermal solution up to the values less than amorphous silica solubility.

CHEMICAL COMPOSITION OF HYDROTHERMAL SOLUTION AT THE MUTNOVSKOE FIELD

Mutnovskoe field is located 70 km southward of Petropavlovsk-Kamchatsky city (Kiryukhin A.V.,
1996). Hydrothermal system consists of two main parts. There is a steam-and-water mix in the upper part and there is a hot water under the temperature of 240-300°C in the lower one. About 60 wells have been drilled at this field, and one third of them are production wells. Capacity of electric power generation of Mutnovskoe field was evaluated up to 200 MW.

“Geotherm” SC, “Nauka” SC and “Kaluga’s turbine plant” SC worked out the technical projects of Verkhne-Mutnovsky geothermal electric power plant with 12 MW and Mutnovsky GeoPP with 50 MW. According to the projects these geothermal plants have the system of separate reinjection in wells under the pressure of 4.0 bar and the temperature of 143°C. Reinjection system of Mutnovskoe plants needs in testing and improving.

Average silica content SiO$_2$ in the separate of Mutnovskoe field wells is 780 mg/kg. Typical chemical composition of the separate (well 014 near Dachny area) is the following (mg/kg): NH$_4^+$ -0.7, Na$^+$ -239.9, K$^+$ -57.0, Ca$^{2+}$-4.0, Mg$_{2+}$-0.24, Cl$^-$ -291.1, SO$_4^{2-}$-124.9, HCO$_3^-$-43.9, CO$_3^{2-}$-18.6, F$^-$ -1.6, H$_2$BO$_3$-65.3, Li$^+$-1.6, SiO$_2$-800.

In the previous work (Kashpura V.N., Potapov V.V., 2000) the types of solid deposits formed at the Mutnovskoe field were researched. Samples were selected from wells, separators, evaporators, turbines, heat-exchangers and pipelines. It was established that the silica SiO$_2$ weight content in these samples was 70-90%, and the bulk of silica had an amorphous structure. Majority of the X-Ray spectrums of the solid samples had amorphous halo maximums in the range of 3.87-4.12 A°. There were weakly expressed pics of some low temperature minerals in some X-Ray spectrums. Weight portion of quartz in different deposits types was (0.1-4.9)%. The following minerals were revealed in the samples by X-Ray and thermochemical analyses: pyrite FeS$_2$, hematite Fe$_2$O$_3$, maghemite, goethite FeO(OH), halite NaCl, gypsum CaSO$_4$.2H$_2$O, thenardite Na$_2$SO$_4$, quartz SiO$_2$, opal SiO$_2$:xH$_2$O.

In the previous work the ranges of sizes (5-15 A°) and the concentration (10$^{16-17}$cm$^{-3}$) of silica colloidal particles in solution were determined and the growth rate of deposits in reinjection wells under conditions of Verkhne-Mutnovsky GeoPP was evaluated. There was shown the necessity of chemical treatment of separate before reinjection (alkalization, acidification).

### Electrochemical Treatment with Different Metal Electrodes

Electrochemical treatment tests were conducted with the samples of separate solution from the well 014 of Mutnovskoe field. The samples were selected from the evaporator discharge at the temperature of 66-72°C. The treatment of a hot solution in the field conditions and of a cooled solution in the laboratory was done.

Electrical scheme of the tests included a source of direct current, a voltmeter and an electrocoagulator. The value of voltage ranged within 4-30 V, current strength- 0.1-3.0 A, current density- 75-112 A/m$^2$, electric field strength- 400-1100 V/m, the temperature of solution- 20-60°C. Electrodes made of aluminium, stainless steel, steel with zink covering and copper were tested.

A cylindrical electrocoagulator with a convex bottom and plastic support had the diameter of 9.1 cm and the height of 24.5 cm. The walls were made of transparent polythene. Continuous metal electrodes made of flat rectangular plates were fixed by two pairs of isolating and mobile inserts. The distance between plates was regulated by these inserts. The area of a part of electrodes plates shipped in a solution was S=0.0133 m$^2$ (0.157m×0.085m). The volume of solution treated in the electrocoagulator was 1 liter.

During the electrochemical treatment in the samples of solution some processes were observed: changing of water colour, increasing of solution temperature, silica coagulation and flakes forming, anod bubbling, convection, electric flotation and forming the foamy flakes mass on the solution surface.

After the treatment ending flakes settled on the vessel’s bottom and then they were separated by rough filter. Then silica SiO$_2$ and trivalent aluminium Al$^{3+}$ concentrations, solution pH were determined. Silica concentration was analyzed by yellow molybdate method with adding ammonium molybdate (NH$_4$)Mo$_7$O$_{24}$·4(H$_2$O)). Optical density of the silica-molybdate complexes in the coloured solution was measured by photocolorimeter. Total silica content in supersaturation solution was analyzed after the preliminary samples heating and adding of alkali NaOH. Trivalent aluminium Al$^{3+}$ concentration was determined with the using of trilon B after the preliminary titrate of iron ions. Trilon B is two-natrium salt of diamine tetraacetic acid forming strong complexes with ions of two-trivalent metals.

Solution temperature increasing during the electrochemical treatment was related with electric...
power losses $Q_{EL}$, according to the following equations:

$$C_p \Delta t = Q_{EL} = U I t_{ET}.$$  (1)

where $\Delta t$ is a change of solution temperature $t_0$, $U$ is an electrodes voltage, $I$ is a current strength, $t_{ET}$ is a treatment duration, $C_p$ is an isobaric heat capacity of 1 kg of water, J/K. Depending on current strength and treatment duration the temperature of solution increased up to (0.1-5.0)$^\circ$C.

Solution and precipitate colour after the treatment depended on electrodes material and on duration of electrodes using. After the using of electrodes made of steel with zinc covering solution colour became yellow, brown or green. The treatment by stainless steel led to black colour of solution, copper electrodes - to blue-green colour. The treatment by stainless steel electrodes didn’t change the colour of solution.

The size of precipitated material was evaluated from the velocities of flakes sedimentation. The equivalent flakes size $d_s$ corresponded to these velocities in Stokes’s regime was determined by the following equation:

$$d_s = (18 \mu u / \Delta \rho g)^{0.5},$$  (2)

where $u$ is a velocity of flakes settling, $\mu$ is a dinamic viscosity of water, $\Delta \rho$ is a difference of silica and water density, $g$ is a gravity acceleration.

The size of flakes precipitated in experiments with steel electrodes was in the range of $d_s=(2-5.5)$ $\mu$m. Flakes precipitated after the treatment with copper electrodes had the size of 33.7 $\mu$m. Flakes precipitated after the aluminium electrodes treatment had equivalent size from 34 to 80 $\mu$m and the settling velocity of 13-20 mm/min. The settling time of flakes with such sizes in a vessel with the height of 20 cm under the temperature of 20$^\circ$C was about 10-15 minutes.

The rate of silica coagulation was the greatest in the experiments with aluminium electrodes. Under the aluminium electrodes treatment with a current strength of I=1.5 A within 30 min total content of silica in the solution was 3.1 mg/kg, and in the solution treated with steel electrodes- 81 mg/kg. It confirmed higher coagulation ability of aluminium hydroxide Al(OH)$_3$ in comparison with the compounds of iron ions Fe$^{2+}$ and copper ions Cu$^{2+}$.

Silicate, X-Ray and thermochemical analyses of the samples precipitated after the electrochemical treatment were done. Chemical composition of the sample AK7 precipitated after the treatment with steel electrodes and AK7c precipitated with aluminium electrodes are shown in the Table 1.

<table>
<thead>
<tr>
<th>Compound</th>
<th>AK7 (%)</th>
<th>AK7c (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>51.8</td>
<td>67.1</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>(-)</td>
<td>0.3</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>0.38</td>
<td>1.64</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>18.42</td>
<td>7.46</td>
</tr>
<tr>
<td>FeO</td>
<td>1.80</td>
<td>(-)</td>
</tr>
<tr>
<td>MnO</td>
<td>(-)</td>
<td>0.03</td>
</tr>
<tr>
<td>MgO</td>
<td>2.24</td>
<td>0.03</td>
</tr>
<tr>
<td>CaO</td>
<td>4.12</td>
<td>0.15</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.42</td>
<td>6.41</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**ELECTROCHEMICAL TREATMENT UNDER VARIOUS CURRENT STRENGTH**

The samples of separate solution were treated under various current strength I=0.5-1.5 A with aluminium electrodes in the laboratory $(t_{ET}=20^\circ$C). On the base of these experimental data the range of current strength values optimum for silica extraction technology was allocated: I=0.5-1.5 A. The dependence of the total silica content SiO$_2$ $C_t$ on treatment duration $t_{ET}$ under the current strength of 0.5, 1.0 and 1.5 A is shown in the Table 2.

<table>
<thead>
<tr>
<th>Treatment duration, $t_{ET}$, min</th>
<th>I=0.5 A</th>
<th>I=1.0 A</th>
<th>I=1.5 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{ET}=0$ min</td>
<td>817.5</td>
<td>819</td>
<td>819</td>
</tr>
<tr>
<td>5 min</td>
<td>667</td>
<td>681</td>
<td>631</td>
</tr>
<tr>
<td>10 min</td>
<td>713</td>
<td>461</td>
<td>341</td>
</tr>
<tr>
<td>15 min</td>
<td>596</td>
<td>247</td>
<td>114</td>
</tr>
<tr>
<td>20 min</td>
<td>419</td>
<td>94</td>
<td>46</td>
</tr>
<tr>
<td>25 min</td>
<td>289</td>
<td>61</td>
<td>18</td>
</tr>
<tr>
<td>30 min</td>
<td>101</td>
<td>41</td>
<td>8</td>
</tr>
</tbody>
</table>

We revealed the nonlinearity of the process of silica precipitation by electrochemical treatment in a supersaturated hydrothermal solution with a high total silica content of 600-800 mg/kg and more. The
The specific rate of aluminium anode dissolving was calculated on the base of famous mathematical model presented in the work of Kulsky L. A., Grebenyuk V. D., Savluk O. S., 1987:

$$\text{lg}(\text{Van}) = b_0 + \sum_{i} b_i X_i + \sum_{ij} b_{ij} X_i X_j,$$

where $b_0$ is another variable from the model, $X_i$ are current density, $\text{mg eqv/litre}, T$ is an absolute solution temperature, $?$, $j$ is a current density, %/dm$^2$, $b_i$, $b_{ij}$ are constant coefficients (they are presented in the work of Kulsky L. A. et al., 1987).

Solution pH, temperature of solution and current density were the factors influencing on the rate of dissolving considerably. Anions concentrations in
process wasn’t taken into account.

The dissolving rate of aluminium cathode under qualified conditions was 3-4 times less than the rate of anode dissolving and the contribution of this process wasn’t taken into account.

Table 3. Dissolving rate of aluminium anode $V_{AL}(mg/min)$, $S=1.334 dm^2$

<table>
<thead>
<tr>
<th>Current strength I</th>
<th>Solution temperature $t_s$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 A</td>
<td>20°C, 3.86; 70°C, 5.10; 100°C, 4.75</td>
</tr>
<tr>
<td>1.0 A</td>
<td>20°C, 5.69; 70°C, 5.42; 100°C, 4.55</td>
</tr>
<tr>
<td>1.5 A</td>
<td>20°C, 7.10; 70°C, 5.58; 100°C, 4.41</td>
</tr>
</tbody>
</table>

At a low temperature of solution ($20^0$C) the rate of anode dissolving became larger with current strength increasing, and at a high temperature ($100^0$C) it reduced (Table 3). Therefore we concluded that the treatment of a hot separate (60-100°C) is better to be made under a low value of current strength ($1.0$-$0.5$ A) because the energy of consumption for treatment was far lower than under $I=1.5$ A.

The calculations showed that under a low solution temperature ($20^0$C) the acidification of solution from pH=8.9 to pH=8.0 led to dissolving rate increasing. On the contrary, under high temperatures alakalization increased the rate of dissolving and it became larger when current strength became smaller. It must be taken into account for the development of silica extraction technology from the hydrothermal separate.

On the base of the calculations $V_{AL}$ (Table 3) the amount of aluminium $Al$ needed for precipitation of 1 gram of silica $SiO_2$ was evaluated. Under the current strength of 1.0 A and the solution temperature of $20^0$C aluminium amount was 155.1 mg/g, under $t_s=70^0$C - 147.8 mg/g, under $t_s=100^0$C - 124.1 mg/g. Aluminium losses increased with current reducing. In accordance with the data of process duration, energy and coagulant losses we concluded that the optimum value of current strength for silica extraction by electrochemical treatment was 1.0 A.

ELECTROCHEMICAL TREATMENT OF A HOT SEPARATE

The quantity of electric energy consumed for treatment expressed by equation (5) depended on electric resistance of electrocoagulator R. Electrocoagulator construction, current strength and the temperature of solution influenced on the resistance R value. Under the temperature of $20^0$C and the current strength of 1.5 A coagulator with aluminium electrodes had the resistance of 7.0-$7.3 \Omega$, under $I=1.0$ A - $R=8.2 \Omega$, under $I=0.5$ A - $R=8.6-10 \Omega$.

To study the resistance dependence $R$ on the temperature a number of tests with a hot separate was conducted. For it a hot solution with an initial temperature of $66^0$C was taken into a vessel of 10 litres volume. Then the samples of a cooled separate of 1 liter volume were withdrawn from this vessel and they were treated by direct current with the strength $I=1.5$ A and treatment duration $t_{ET}=10-15$ minutes. The value of coagulator resistance $R$ depended on the temperature $t_s$ in the following way: $55^0$ - 4.33 $\Omega$, $43^0$ - 5.0 $\Omega$, $36^0$ - 5.33 $\Omega$, $30^0$ - 5.66 $\Omega$, $27^0$ - 6.0 $\Omega$, $23^0$ - 6.33 $\Omega$, $20^0$ - 7.0 $\Omega$.

According to the tests data the resistance $R$ reduced monotonously with the temperature increasing: the value $R$ decreased in 1.6 times with the increasing $t_s$ from 20 to $60^0$C. Electric conductivity increased from 1.07 ($\Omega$·sm)$^{-1}$ to 1.71 ($\Omega$·sm)$^{-1}$ correspondently. Energy $Q_{ET}$ consumed for treatment of a hot separate became smaller. The increasing of the conductivity of hydrothermal solution was explained by the growth of ion mobility at the high temperature. The relative contribution to the conductivity of Na$^+$ ion was 33.2 %, K$^+$ -6.8 %, Cl$^-$ -39.8 %, HCO$_3^-$ -2.0 %, SO$_4^{2-}$ -13.2 %, CO$_3^{2-}$ -2.7 %.

On the base of tests with a hot separate we compared the rate of silica precipitation by electrochemical treatment at high temperatures with the low temperatures rate. For this comparison it was made the treatment of two samples of hydrothermal solution under the temperature of $58-55^0$C and $20^0$C and the current strength of 1.0 A. For reducing of heat losses during a hot solution treatment the coagulator was put into the vessel of much greater volume (12 litres) filled up with a hot separate at $60^0$C. The solution temperature reduced after 15 minutes of treatment insignificantly: from $58^0$C to $55^0$C.

Before the treatment total silica $SiO_2$ content $C_t$ was 775 mg/kg. After the treatment the concentration $C_t$ in the hot sample was 323 mg/kg and it was 264 mg/kg in the sample treated under the temperature of
We made a conclusion that the process of silica precipitation by electrochemical coagulation in the hydrothermal solution under the temperature of 20°C had a greater rate than under the temperature of 50-60°C: precipitation rate was 10-15% greater in the case of a cold solution treatment. But the electric resistance during a cold solution treatment was considerably higher than in a hot solution: for 61.6%. So it should be expected the increasing of energy consumption during a cold separate treatment.

**INFLUENCE OF THE DISTANCE BETWEEN ELECTRODES**

Influence of the distance between electrodes plates on effectiveness of treatment was studied. For it electrochemical treatment was made with three different positions of electrodes in the electrocoagulator: the electrodes were set at the distance \( h_{el} = 5, 10 \) and \( 15 \) mm. The treatment was made under the current strength of \( 1.0 \) A with treatment time \( t_{ET} = 5, 10, 12.5, 15 \) and \( 17.5 \) minutes.

These tests showed that the distance \( h_{el} \) between the electrodes in the range of 5-15 mm didn’t considerably influence on silica precipitation rate. The concentration \( C_i \) in the treated samples of these three series of tests differed under \( t_{ET} = 5 \) minutes in 1.06 times, under \( t_{ET} = 10 \) minutes in 1.23 times, under \( t_{ET} = 12.5 \) minutes in 1.06 times, under \( t_{ET} = 15.0 \) minutes in 1.27 times. Values of solution pH of the treated solution samples were also differed a little.

The main factors influenced on the silica coagulation and precipitation processes were aluminium anode dissolving rate and the rate of aluminium diffusion from the anode plates to the solution volume. Both factors didn’t depend on the distance between the electrodes.

The electrocoagulator resistance \( R \) became greater with the increasing of the distance between the electrodes \( h_{el} \): \( h_{el} = 5 \) mm- \( R = 4.5 \) \( \Omega \), \( h_{el} = 10 \) mm- \( R = 7.7 \) \( \Omega \), \( h_{el} = 15 \) mm- \( R = 10.2 \) \( \Omega \). Therefore, it could be concluded that the quantity of energy \( Q_{UT} \) needed for electrochemical treatment reduced with the distance \( h_{el} \) decreasing approximately linearly. An optimum distance between the electrodes was 10 mm.

**PARAMETERS OF A PILOT ELECTROCOAGULATOR**

On the base of these researchings the calculations of the parameters of a pilot electrocoagulator necessary for silica extraction from a flow of the hydrothermal separate were made.

It was suggested that a pilot plant must process of a continuous flow of separate from the well 014 with mass rate of 1.0 kg/s. The calculations were also made for the flow of 50 kg/s from the reinjection system of Verkhne-Mutnovsky GeoPP. The current strength needed for electrochemical treatment of every kilogram of solution in a coagulator was \( I = 1.0 \) A. Treatment duration was \( t_{ET} = 15.0 \) minutes, it corresponded to silica \( \text{SiO}_2 \) concentration reducing from 800 to 250 mg/kg. The temperature of treated solution was supposed within 60-80°C.

The scheme of processing included four stages: 1. ageing of a hot solution in a tank during 15 minutes for ending polymerization reaction and forming of colloidal silica; 2. electrochemical treatment of solution in coagulator during 15 minutes; 3. silica flakes sedimentation and solution clarification in a settling tank during 10-15 minutes; 4. filtration of clarified solution through the filter for a finelly removal of small-dispersed material.

The sizes of ageing tank for the processing of a flow with the rate of 1 kg/s were: the height was 0.5 m, the width was 1.0 m, the length was 2.0 m, the tank’s volume was 1.0 m³. The sizes of a settling tank for the flow of 1 kg/s were the following: the height was 0.3 m, the width was 1.5 m, the length was 2.0 m, the tank’s volume was 0.9 m³.

The coagulator was suggested to be consisted of the same sections which quantity \( N_S \) depended on the separate flow rate. The section had the summary compartments’ length of 5.0 m, the area of cross-section was 1.0 dm² (0.1mx0.1m), the section volume was 50 dm³. Separate mass rate for one section with such construction was 55.5 g/s, velocity of solution movement relatively to the electrodes plates was 5.5 mm/s.

Aluminium electrodes plates were installed parallelly, electrodes plates width was 0.1 m, summary area of anode and cathode plates in one section was 1.0 m². The distance between the electrodes plates was \( h_{el} = 10.0 \) mm, and the electrodes resistance was \( U = 6.8 \) V. Summary aluminium losses from the anode plates of one section under the solution temperature of 70°C, \( \text{pH} = 8.0 \), \( I = 1.0 \) A were 207 mg/min according to the equation (6).

Sections quantity \( N_S \) in a coagulator with the flow rate of 1.0 kg/s was 18, total volume of sections was 0.9 m³, the length and the width were about 0.4 m. Summary area of the electrodes plates in 18 sections...
was $S=18.0 \text{ m}^2$, anode aluminium losses reached the value of $V_{al}=1.96 \text{ t/year}$. Current strength corresponded to a simultaneous treatment of 900 kg of solution in a coagulator was $I=900 \text{ A}$, summary electric power consumed for treatment was $N_{el}=6.15 \text{ kW}$. The pilot plant productivity was evaluated as 17.3 t/year of the geothermal silica $\text{SiO}_2$.

The coagulator parameters for treatment of separate flow with mass rate of 50.0 kg/s in the conditions of Verkhne-Mutnovsky GeoPP were the following: quantity of sections was $N_S=900$, total volume was $45.0 \text{ m}^3$. Summary square of the electrodes plates was $S=900.0 \text{ m}^2$, anode aluminium losses were $V_{al}=98.0 \text{ t/year}$. Calculated value of the electric power capacity needed for treatment under the current strength of $I=145000 \text{ A}$ was $N_{el}=307.5 \text{ kW}$. It corresponded to 2.5% of the capacity of the whole Verkhne-Mutnovsky GeoPP (12 MW). Plant productivity was evaluated as 865.0 t/year of geothermal silica.

For economic analysis of the projects with electrochemical treatment of the hydrothermal separate for silica extraction it must be taken into account several factors: 1. profit losses caused by interruption of electric power generation in the case of solid deposits formation in the reinjection wells, expensive measures for removal of solid deposits from the well or drilling and building of a new reinjection well; 2. profit from generation of additional electric and heat energy; 3. profit from minerals extraction (amorphous silica, the compounds of lithium Li, boron B, arsenic As and others).

**CONCLUSIONS**

1. On the base of the experimental data optimum values of some technology parameters useful for development of the technology of silica extraction from the hydrothermal separate were evaluated: current strength, voltage, consumed electric power, duration of electrochemical treatment, coagulant losses, equivalent flakes size of the coagulated silica and the time of solution clarification after the treatment.

2. The highest treatment effectiveness was reached during the experiments with aluminium electrodes. The experiments confirmed that aluminium hydroxide $\text{Al(OH)}_3$ had the greatest coagulation ability in a water solution of hydrothermal separate in a comparison with iron ions $\text{Fe}^{2+}$, $\text{Fe}^{3+}$ and copper ion $\text{Cu}^{2+}$ compounds.

3. The samples of the material precipitated as a result of electrochemical treatment had an amorphous structure. Maximums of amorphous haloes in the spectrums of X-Ray analysis were situated in the range of 3.7-4.0 $\text{Å}$. A relation of a coagulant (Al, Fe) weight portion to a weight portion of precipitated silica $\text{SiO}_2$ in these samples was 0.1-0.25.

4. On the base of experimental data we found the theoretical function expressing the dependence of the quantity of precipitated silica on the duration of electrochemical treatment with aluminium electrodes under different current strength. With the help of this equation it could be possible to calculate the quantity of the electric energy and the coagulant (Al) needed for silica precipitation.

5. During the treatment tests with a hot separate ($t_s=600 \text{°C}$) effectiveness of silica precipitation under high temperatures was researched. Relation between the electric conductivity of hydrothermal solution and the temperatures in the range of (20-600 °C) was determined. It was obtained that solution conductivity increased with the increasing of temperature and ions mobility.

6. The researchings showed that electrochemical coagulation could be one of the stage of hydrothermal separate treatment before the reinjection in a combination with other known methods (for instance, lime $\text{Ca(OH)}_2$ adding). The results of experiments confirmed the necessity of the further studying of the electrochemical coagulation process in high temperature hydrothermal solutions.

**REFERENCES**


