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Purification of process solutions from mercury by sorption

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Abstract: At JSC "Uralelectromed", selenium-containing raw materials and industrial products are processed, resulting in solutions containing a mixture of mercury with concentrations as follows (g/dm^3): 157–210 Se; 0.004–0.02 Hg; 0.15–0.20 Te; 2–3 As; 0.15–0.20 Sb; and 45–50 S. To produce branded selenium, the mercury concentration in the solution must be kept below 0.001 g/dm^3. Various methods, such as hydrometallurgical and electrochemical processes, are known for mercury purification from solutions. JSC "Uralelectromed" has selected sorption technology for mercury removal using the weak-base macroporous anionite Lewatit MP-68 (Germany), which allows for control over the degree of solution purification. In pursuit of import substitution for the Western European sorbent Lewatit MP-68, we investigated several pre-selected industrial sorbents for extracting mercury anionic complexes produced in Russia (AM-2B, AN-31, AV 17-8, VP-3Ap), China (Seplite MA 940 and LSC 710), and India (Tulsion CH-95 and CH-97). Initially, in static mode, we determined the distribution coefficient (C_d), the degree of element extraction (ε), the static exchange capacity of the resins (SEC, g/dm^3), and the mercury/selenium separation coefficient ($D_{Hg/Se}$) which led to the selection of the best samples: AV 17-8, Seplite MA 940, AM-2B, and CH-97, with SEC values of 0.95–0.97 g/dm^3 (SEC = 0.98 g/dm^3 of resin Lewatit MP-68). Subsequently, in dynamic mode, we ranked the ionites by decreasing dynamic exchange capacity (DEC / TDEC): AV 17-8 ≥ Lewatit MP-68 > AM-2B > Seplite MA 940 > Tulsion CH-97. Resins AV 17-8, Seplite MA 940, and AM-2B demonstrated similar dynamic sorption characteristics; under comparable conditions, mercury breakthrough occurred after processing at least 950 specific volumes of the initial solution. In contrast, with Lewatit MP-68 ionite, mercury breakthrough occurred after no more than 750 specific volumes, indicating the need to increase the number of sorption steps in the solution purification cascade. Considering the totality of ion-exchange properties, for further industrial testing, it is recommended to use the domestically produced resin AV 17-8 instead of the foreign sorbent Lewatit MP-68 in the sorption purification process of selenic acid to remove mercury, thereby ensuring the production of branded selenium.

Keywords: mercury, selenium, resin, sorption, static exchange capacity, dynamic exchange capacity, hydrometallurgical purification.

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Очистка технологических растворов от ртути сорбцией

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Аннотация: При переработке в АО «Уралэлектромедь» селенсодержащего сырья и промпродуктов образуются растворы, содержащие примесь ртути, г/дм^3: 157–210 Se; 0,004–0,02 Hg; 0,15–0,20 Te; 2–3 As; 0,15–0,20 Sb; 45–50 S. Для получения марочного селена концентрация ртути в растворе не должна превышать 0,001 г/дм^3. Известны различные методы очистки растворов от ртути: гидрометаллургические, электрохимические и др. В АО «Уралэлектромедь» выбор сделан в пользу сорбционной технологии удаления ртути на слабоосновном макропористом анионите Lewatit MP-68 (Германия), позволяющей управлять степенью очистки растворов. Для обеспечения замещения западноевропейского сорбента (Lewatit MP-68) проведено исследование ряда предварительно отобранных промышленных сорбентов анионных комплексов ртути производства РФ (АМ-2Б, АН-31, АВ 17-8, ВП-3Ап), Китая (Seplite MA 940 и LSC 710), Индии (Tulsion CH-95 и CH-97). На первой стадии в статическом режиме определены коэффициент распределения ($K_р$), степень извлечения элементов (ε), значения статической обменной емкости смол (СОЕ, г/дм^3), коэффициент разделения ($D_{Hg/Se}$), на основании которых отобраны лучшие образцы: АВ 17-8, Seplite MA 940, АМ-2Б, CH-97 с величинами СОЕ = 0,95÷0,97 г/дм^3 (у смолы Lewatit MP-68 СОЕ = 0,98 г/дм^3). На второй стадии в динамическом режиме установлено следующее: по величине ДОЕ/ПДОЕ иониты расположены в убывающий ряд: АВ 17-8 ≥ Lewatit MP-68 > > АМ-2Б > Seplite MA 940 >> Tulsion CH-97. Смолы АВ 17-8, Seplite MA 940, АМ-2Б близки по своим динамическим сорбционным характеристикам: в сопоставимых условиях проскок по ртути наступает после пропускания не менее 950 уд. объемов исходного раствора. Для сравнения: на ионите Lewatit MP-68 проскок по ртути наступает после пропускания не более 750 уд. объемов, что требует увеличения числа ступеней сорбции в каскаде очистки растворов. По совокупности ионообменных свойств для дальнейшего исследования в режиме промышленных испытаний рекомендуется использовать смолу АВ 17-8 отечественного производства вместо зарубежного сорбента Lewatit MP-68 в технологической схеме сорбционной очистки селенистой кислоты от ртути с целью обеспечения получения марочного селена.

Ключевые слова: ртуть, селен, смола, сорбция, статическая обменная емкость, динамическая обменная емкость, гидрометаллургическая очистка.

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Introduction

At JSC "Uralelectromed", raw materials and industrial products containing selenium are processed, resulting in solutions with varying concentrations of impurities, g/dm^3: 157—210 selenium (Se); 0.004—0.02 mercury (Hg); 0.15—0.20 tellurium (Te); 2—3 arsenic (As); 0.15—0.20 antimony (Sb); and 45—50 sulfur (S). For production of branded selenium, the concentration of mercury in the solution should not exceed 0.001 g/dm^3 [1].

Various methods have been developed to purify solutions of mercury. These include the electrochemical reduction, which removes over 92 % of mercury as an Hg—Cu alloy, followed by the thermal desorption of mercury from the spent cathode [2]. Sorption techniques, utilizing microporous niobium (AM-11) and vanadium (AM-14) silicates, can adsorb approximately 160 mg/g of mercury [3]. Combined electron-beam and adsorption treatments on cellulose, carboxymethylcellulose, and starch remove 98 % of Hg(II) [4]. Activated carbon, alloyed with sulfur, has shown the ability to absorb up to 187 mg/g of mercury [5]. Induction adsorption of HgO on an alkaline sorbent with active chalcogen-based centers [6]; sorption removal of over 80 % of elemental mercury Hg^0 on H_2S modified magnetospheres (S—MS) [7; 8], and mercury desorption techniques via thermal treatment and plasma method [9] have been reported. Photocatalytic oxidation of Hg^0 enables up to 87 % removal of mercury [10]. The photothermal aerogel method enables the potential for achieving complete purification from heavy metal ions [11]. Cementation of mercury ($HgCl_4^{2-}$) from chloride medium using metallic zinc, iron, and aluminum results in a final solution with $8 \cdot 10^{-2}$ g/dm^3 of mercury [12]. In acidic solutions, mercury complexes such as $[Hg(SO_3)_2]^{2-}$, $[Hg(SO_3)_3]^{4-}$, $[Hg(SO_3)_4]^{6-}$ [13], form and are adsorbed on carbon-containing materials [14]. Sulfur copolymers with micro- and macroporous structures actively interact with mercury compounds in solution [15], forming multinuclear Hg—S sulfide complexes [16—18]. The presence of chloride ions also leads to the formation of mercury complex compounds: $HgCl^+$, $HgCl_3^-$, $HgCl_4^{2-}$ [19—26].

JSC "Uralelectromed" selected the sorption technology using the weak-base macroporous anionite Lewatit MP-68 from Germany for mercury removal. This technology allows for a high degree of solution purification using compact equipment. It is highly reliable, easy to operate, and remains effective regardless of fluctuations in concentration and hydraulic pressure. To facilitate the import substitution of the Western European reagent Lewatit MP-68, we explored several pre-selected industrial sorbents designed for extracting mercury anionic complexes. These sorbents are produced in Russia (AM-2B, AN-31, AV 17-8, VP-3Ap), China (Seplite MA 940 and LSC 710), and India (Tulsion CH-95 and CH-97). The characteristics of these sorbents are detailed in Table 1.

The objective of this study was to identify a sorbent that could serve as an alternative to Lewatit MP-68 and to determine the optimal parameters for purifying selenic acid solutions from mercury to achieve a residual concentration not exceeding 0.001 g/dm^3 Hg.

Methods

The resins tested were pre-treated prior to their use, following these steps: they were soaked in dis-

Tabl. 1. **Characteristics of the studied resins**

Таблица 1. Характеристики исследуемых смол

Description	Type	Purpose according to the data sheet
Lewatit MP-68	Weak-base macroporous anionite based on a styrene-divinylbenzene copolymer with monodisperse granule distribution	Desalinization Treatment of rinse water in galvanic processes Demineralization of water with a high content of humic acids
Seplite MA 940	Macroporous polystyrene weak-base anionic resin Weak-base anionite (tertiary amine functional groups)	Removal of heavy non-ferrous metals from industrial solutions High resistance to osmotic shock Removal of natural organic matter
Seplite LSC 710	Ion-exchange chelating resin with iminodiacite functional groups	Removal of heavy metals from solutions
Tulsion CH-95 Tulsion CH-97	Chelate resin (Cl^-) With functional groups (iminodiacetic acid, phosphoric acid, thiuronium, thiol)	Selective sorption of metals from aqueous and organic solutions at different pH Removal of heavy (Fe, Cu, Ni, Zn, Cr, Co, Mn, Mo, Cd, Hg) and precious (Pt, Pd, Au, Ag, Rh) metals
AV 17-8	Strong-base sorbent with a gel structure Functional group – quaternary trimethylammonium groups of basic nature Matrix – styrene-divinylbenzene	Water softening and desalination at thermal and nuclear power plants and in boiler houses Purification of process solutions and wastewater Separation and sorting of non-ferrous metals
AM-2B	Benzyldimethylammonium and dibenzyldimethylammonium functional groups	Selective extraction of cyanide anionic gold complexes
AN-31	Weak-base resin with functional groups including quaternary trimethylammonium, secondary and tertiary aliphatic amino groups	Applications in water treatment, wastewater treatment, chemical and hydrometallurgical industries Separation and sorting of non-ferrous metals
VP-3Ap	Strong-base macroporous anionite based on a copolymer 4-vinylpyridine and divinylbenzene	Extraction of heavy non-ferrous metals from various media, in particular, thorium and plutonium from nitric acid systems

tilled water for 24 h, then washed with a 5 % NaOH solution to pH = 10÷12. Afterward, they were rinsed with water until a neutral pH was achieved. This was followed by treatment with a 5—15 g/dm^3 solution of H_2SO_4, and finally, they were washed with water to pH = 2÷5.

To determine the static exchange capacity of the resins (SEC, g/dm^3), an initial solution of 0.1 dm^3 with the following composition, g/dm^3: 208.3 Se; 0.02 Hg; 0.15 Te; 2.9 As; 0.16 Sb; 49 S) was brought into contact with 0.002, 0.005, and 0.010 dm^3 of sorbents. The mixture was stirred for 72—96 h. The filtrates after sorption were analyzed, and the following values were calculated: SEC, distribution coefficient (C_d), elements extraction degree (ε), and the mercury/selenium separation coefficient ($D_{Hg/Se}$), as seen in Table 2:

$$\mathrm{SEC} = (C_{init} - C_{equil})V_{solut}/V_{sorb}, \tag{1}$$

where C_{init} and C_{equil} are the initial and equilibrium concentrations of Hg in the solution, respectively, g/dm^3; V_{solut} and V_{sorb} are the volumes of the sorbent and solution, respectively, dm^3;

$$C_d = \mathrm{SEC}/C_{equil}, \tag{2}$$

$$\varepsilon = (C_{init} - C_{equil})/C_{init}, \tag{3}$$

$$D_{Hg/Se} = C_d(\mathrm{Hg})/C_d(\mathrm{Se}). \tag{4}$$

To determine the dynamic exchange capacity (DEC, mg/cm^3) and total dynamic exchange capacity (TDEC, mg/cm^3) of the resins, the initial solution (with a composition of 160—170 g/dm^3 Se and 0.004—0.029 g/dm^3 Hg) was passed through 0.020 dm^3 of the test resin loaded into a column at a rate of ~0.020 dm^3/h (1 specific volume). The value of TDEC (mg$_{\text{elem}}$/cm$^3{}_{\text{sorb}}$) was calculated by summing the amount of the element absorbed from each portion of the solution that had passed through the test resin, relative to the volume of the sorbent:

$$\text{TDEC} = \Sigma V_{\text{solut}}(C_0 - C_{\text{outl}})/V_{\text{sorb}}, \qquad (5)$$

where V_{sorb} represents the volume of the sorbent, dm^3, C_0 is the initial concentration of the element, g/dm^3, C_{outl} is the concentration of the element at the column outlet, respectively, g/dm^3, and V_{solut} is the volume of the solution that has passed through the column, dm^3.

Results and discussion

Table 2 presents experimental data on mercury sorption in static mode.

The criteria for selecting the resin were based on achieving the maximum values of SEC and the degree of impurity extraction for mercury (Hg), while minimizing the extraction of the macrocomponent (Se), as indicated by the highest separation coefficient ($D_{\text{Hg/Se}}$).

Tabl. 2. **Values of SEC, ε, C_d and $D_{\text{Hg/Se}}$ for ion exchange resins**

Таблица 2. Значения СОЕ, ε, K_p и $D_{\text{Hg/Se}}$ для ионообменных смол

Name of resin	L : S	SEC, g/dm^3		C_d		Extraction ε, %		Separation coefficient $D_{\text{Hg/Se}}$
		Hg	Se	Hg	Se	Hg	Se	
AM-2B made in Russia	50	0.97	1210.0	1616.7	6.6	97.00	11.62	246
	20	0.40	218.0	1980.0	1.1	99.00	5.23	1793
	10	0.20	168.0	1990.0	0.9	99.50	8.07	2268
AN-31 made in Russia	50	0.00	790.0	0.0	4.1	0.00	7.59	0
	20	0.08	416.0	5.0	2.2	20.00	9.99	2
	10	0.09	138.0	8.2	0.7	45.00	6.63	12
AV 17-8 made in Russia	50	0.96	1285.0	1086.4	7.0	95.60	12.34	154
	20	0.40	544.0	1719.1	3.0	98.85	13.06	572
	10	0.20	292.0	1990.0	1.6	99.50	14.02	1221
Lewatit MP-68	50	0.98	815.0	2077.7	4.2	97.65	7.83	489
	20	0.40	484.0	3980.0	2.6	99.50	11.62	1514
	10	0.20	316.0	1990.0	1.8	99.50	15.17	1113
Seplite MA 940	50	0.95	1085.0	859.1	5.8	94.50	10.42	148
	20	0.39	336.0	1313.3	1.8	98.50	8.07	749
	10	0.20	99.0	1808.2	0.5	99.45	4.75	3624
Seplite LSC 710	50	0.25	790.0	16.7	4.1	25.00	7.59	4
	20	0.23	366.0	27.1	1.9	57.50	8.79	14
	10	0.15	292.0	31.7	1.6	76.00	14.02	19
Tulsion CH-95	50	0.94	790.0	783.3	4.1	94.00	7.59	191
	20	0.40	276.0	2646.7	1.4	99.25	6.63	1865
	10	0.20	390.0	1990.0	2.3	99.50	18.72	864
Tulsion CH-97	50	0.95	1135.0	859.1	6.1	94.50	10.90	140
	20	0.40	504.0	3980.0	2.8	99.50	12.10	1446
	10	0.20	257.0	1990.0	1.4	99.50	12.34	1414
VP-3Ap made in Russia	50	0.78	1260.0	172.2	6.9	77.50	12.10	25
	20	0.36	474.0	190.5	2.6	90.50	11.38	74
	10	0.19	257.0	275.7	1.4	96.50	12.34	196

The anions in the solution that compete for the binding sites on the functional groups of the sorbents are mercury complexes, namely sulfomercurates ($[Hg(SO_3)_2]^{2-}$, $[Hg(SO_3)_3]^{4-}$, $[Hg(SO_3)_4]^{6-}$) and selenic acid anions (H_2SeO_3 with pK = 2.46 and H_2SeO_4 with pK = –3.0). In acidic solutions (pH < 1), only the strong selenic acid anions SeO_4^{2-} are present, with a molecular volume calculated as $V_m = M/\rho = 144.9/2.95 = 49.1$ cm^3/mol. For sulfomercurates of the specifed composition, the molecular volumes are $V_m = 68.4 \div 98.6$ cm^3/mol. Despite their large molecular volumes in comparison to selenic acid anions, the preferential sorption of sulfomercurates was observed. This can be attributed to their higher negative charge, which ensures a stronger interaction with the functional groups of the ion-exchange resins.

Based on the studies conducted and the calculated separation coefficients, domestic samples AV 17-8 and AM-2B, as well as the foreign samples Seplite MA 940 and Tulsion CH-97, were selected for further investigation of sorption under dynamic conditions. These will be compared with the currently used Lewatit MP-68 resin.

Based on the studies conducted and the calculated separation coefficients, domestic samples AV 17-8 and AM-2B, as well as the foreign samples Seplite MA 940 and Tulsion CH-97, were selected for further investigation of sorption under dynamic conditions. These will be compared with the currently used Lewatit MP-68 resin.

During the saturation of the resin, the concentrations of mercury and selenium in the solutions post-sorption varied. The solutions were analyzed using inductively coupled plasma (ICP) methods on a Shimadzu AA-7000 spectrophotometer (Japan). Figure 1 illustrates the graphical relationship between the mercury concentration in the solution after sorption and the volume of the solution that passed through the resin. The results of the DEC and TDEC calculations are presented in Table 3.

The following conclusions can be drawn from the results of mercury sorption from process solutions in dynamic mode:

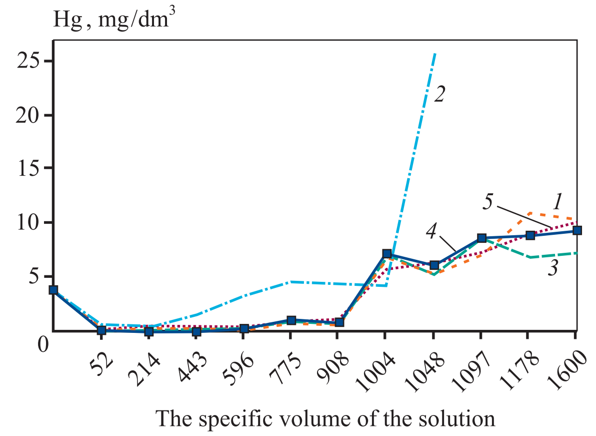

Fig. 1. Mercury concentration in solutions after sorption as a function of the specific volume of the solution passed through the resin

1 – AM-2B; ***2*** – Tulsion CH-97; ***3*** – AV 17-8; ***4*** – Seplite MA 940; ***5*** – Lewatit MP-68

Рис. 1. Концентрация ртути в растворах после сорбции в зависимости от пропущенного удельного объема раствора

1 – АМ-2Б; ***2*** – Tulsion CH-97; ***3*** – АВ 17-8; ***4*** – Seplite MA 940; ***5*** – Lewatit MP-68

1. In terms of the DEC/TDEC values, the resins are ranked in descending order as follows: AV 17-8 ≥ Lewatit MP-68 > AM-2B > Seplite MA 940 >> Tulsion CH-97.

The significant discrepancy between the performance in static mode and the DEC/TDEC for Tulsion CH-97 can likely be attributed to its different functional groups and type of sorbent. It is presumed that in the dynamic mode, the Se macrocomponent displaces the previously sorbed mercury compounds from the resin phase.

2. The resins AV 17-8, Seplite MA 940, and AM-2B display similar dynamic sorption characteristics. Under comparable conditions, a breakthrough in mercury occurs after at least 950 specific volumes of the initial solution have passed through. For comparison, with Lewatit MP-68 resin, mercury breakthrough occurs after

Tabl. 3. **Calculations of DEC/TDEC for mercury**

Таблица 3. Данные расчетов ДОЕ/ПДОЕ по ртути

Name of resin	Sorbed Hg, g	DEC at a breakthrough, mg/cm^3	TDEC, mg/cm^3
AM-2B	0.223	3.4	11.1
Tulsion CH-97	0.029	1.3	1.4
AV 17-8	**0.256**	**3.4**	**12.9**
Lewatit MP-68	0.259	2.6	12.8
Seplite MA 940	0.226	3.2	11.3

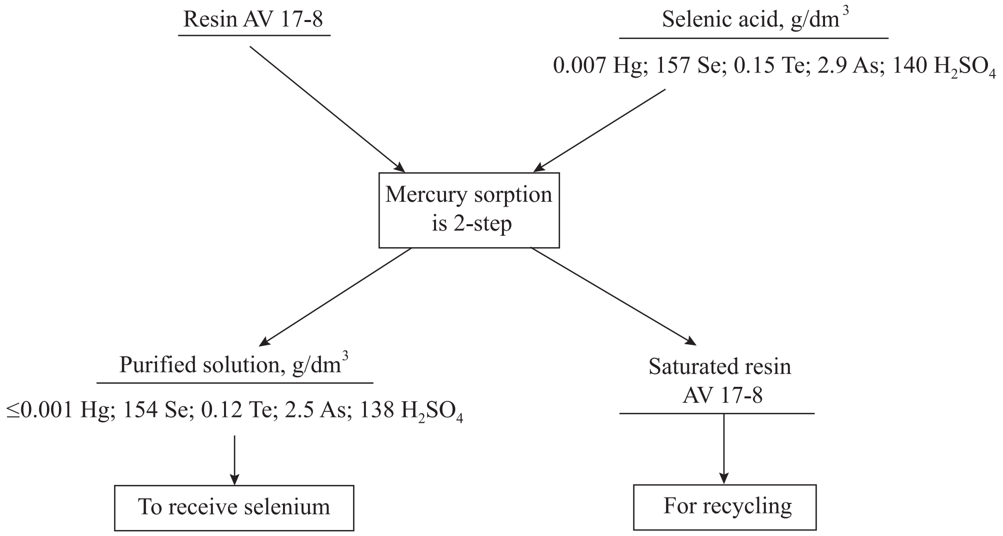

Fig. 2. The basic technological scheme of sorption purification of selenic acid from mercury with resin AV 17-8

Рис. 2. Принципиальная технологическая схема сорбционной очистки смолой АВ 17-8 селенистой кислоты от ртути

no more than 750 specific volumes, indicating that the number of sorption steps in the cascade for solution purification should be increased.

3. Considering the overall ion-exchange properties, it is recommended to use the domestically produced AV 17-8 resin for further tests in an industrial setting to replace Lewatit MP-68 (Germany) in the sorption purification process of selenic acid from mercury. To produce branded selenium, a two-stage sorption process is advisable, as illustrated in Fig. 2. This involves using two columns filled with ionite. If a breakthrough occurs, the first stage is removed for desorption or disposal, the second stage takes its place, and a new column is added to the sequence.

Conclusions

1. To find a replacement for the Lewatit MP-68 ionite currently used for purifying selenic acid solutions from mercury, we reviewed technical literature and selected ionites manufactured in Russia (AM-2B, AN-31, AV 17-8, VP-3Ap), China (Seplite MA 940 and LSC 710), and India (Tulsion CH-95 and CH-97). In the initial static phase, we determined the distribution coefficient (C_d), the degree of elements' extraction (ε), and the static exchange capacity of the resins (SEC, g/dm^3), which led to the selection of the most effective samples: AV 17-8, Seplite MA 940, AM-2B, and Tulsion CH-97, with SEC values of 0.95—0.97 g/dm^3 and a mercury/selenium separation coefficient ($D_{Hg/Se}$) of 1,220—3,620 (for Lewatit MP-68 resin, SEC = 0.98 g/dm^3, $D_{Hg/Se}$ = =1,520).

2. For the resins under study, the following process parameters were established: the volume before a mercury breakthrough, with an initial solution concentration of 4—30 mg/dm^3, was $V_{\text{breakthrough}}$ = 750÷950 specific volumes; DEC / TDEC = 2.6÷3.4/11.1÷12.8 mg/cm^3.

Based on the conducted studies, the ionites were ranged according to their mercury sorption performance: AV 17-8 ≥ Lewatit MP-68 > AM-2B >> Seplite MA 940 >> Tulsion CH-97.

3. Considering the comprehensive sorption characteristics determined, the AV 17-8 resin can be recommended as a substitute for the Lewatit MP-68 resin for industrial testing to identify the optimal parameters for purifying selenic acid solutions of mercury.

4. A process flow scheme for purifying industrial selenium solutions of mercury has been developed and implemented into production. It includes two-stage sorption using AV 17-8 ionite with a specific volumetric flow rate of 0.9—1.1 h^{-1}, processing of the saturated resin, and extraction of selenium from the mercury-purified solution.

References

1. Lebed A.B., Naboichenko S.S., Shunin V.A. Production of selenium and tellurium at "Uralelectromed" OJSC. Ekaterinburg: UrFU, 2015. 112 p. (In Russ.).
   Лебедь А.Б., Набойченко С.С., Шунин В.А. Производство селена и теллура на ОАО «Уралэлектромедь». Екатеринбург: УрФУ, 2015. 112 с.
2. Yang S., Li Z., Yan K., Zhang X., Xu Z., Liu W., Liu Z., Liu H. Removing and recycling mercury from scrubbing

solution produced in wet nonferrous metal smelting flue gas purification process. *Journal of Environmental Sciences*. 2021;(103):59—68.
https://doi.org/10.1016/j.jes.2020.10.013

3. Fabre E., Rocha A., Cardoso S.P., Brandão P., Vale C. Lopes C.B., Pereira E., Silva C.M. Purification of mercury-contaminated water using new AM-11 and AM-14 microporous silicates. *Separation and Purification Technology*. 2020;(239):116438.
https://doi.org/10.1016/j.seppur.2019.116438
4. Ponomarev A.V., Bludenko A.V., Makarov I.E., Pikaev A.K., Kim D.K., Kim Y., Han B. Combined electron-beam and adsorption purification of water from mercury and chromium using materials of vegetable origin as sorbents. *Radiation Physics and Chemistry*. 1997;49(4):473—476.
http://dx.doi.org/10.1016/S0969-806X(96)00148-X
5. Zhang B., Petcher S., Gao H., Yan P., Cai D., Fleming G., Parker D.J., Chong S.Y., Hasell T. Magnetic sulfur-doped carbons for mercury adsorption. *Journal of Colloid and Interface Science*. 2021;(603):728—737.
https://doi.org/10.1016/j.jcis.2021.06.129
6. Pang X., Liu W., Xu H., Hong Q., Cui P., Huang W., Qu Z., Yan N. Selective uptake of gaseous sulfur trioxide and mercury in ZnO—CuS composite at elevated temperatures from SO_2-rich flue gas. *Chemical Engineering Journal*. 2022;(427):132035.
https://doi.org/10.1016/j.cej.2021.132035
7. Xin F., Xiao R., Zhao Y., Zhang J. Surface sulfidation modification of magnetospheres from fly ash for elemental mercury removal from coal combustion flue gas. *Chemical Engineering Journal*. 2022;(436):135212.
http://dx.doi.org/10.1016/j.cej.2022.135212
8. Teng H., Altaf A.R. Elemental mercury (Hg^0) emission, hazards, and control: A brief review. *Journal of Hazardous Materials Advances*. 2022;(5):100049.
https://doi.org/10.1016/j.hazadv.2022.100049
9. Ji Z., Huang B., Gan M., Fan X., Wang Y., Chen X., Sun Z., Huang X., Zhang D., Fan Y. Recent progress on the clean and sustainable technologies for removing mercury from typical industrial flue gases: A review. *Process Safety and Environmental Protection*. 2021;(150):578—593.
https://doi.org/10.1016/j.psep.2021.04.017
10. Jia T., Luo F., Wu J., Chu F., Xiao Y., Liu Q., Pan W., Li F. Nanosized Zn—In spinel-type sulfides loaded on facet-oriented CeO_2 nanorods heterostructures as Z-scheme photocatalysts for efficient elemental mercury removal. *Science of the Total Environment*. 2022;(813):151865.
https://doi.org/10.1016/j.scitotenv.2021.151865
11. Meng F., Umair M.M., Iqbal K., Jin X., Zhang S., Tang B. Rapid fabrication of noniridescent structural color coatings with high color visibility, good structural stability, and self-healing properties. *ACS Applied Materials Interfaces*. 2019;11(13):13022—13028.
https://doi.org/10.1021/acsami.9b01522
12. Anacleto A.L., Carvalho J.R. Mercury cementation from chloride solutions using iron, zinc and aluminium. *Minerals Engineering*. 1996;9(4):385—397.
https://doi.org/10.1016/0892-6875(96)00025-8
13. Gladyshev V.P., Levitskaya S.A., Filippova L.M. Analytical chemistry of mercury. Moscow: Nauka, 1974. 231 p. (In Russ.).
Гладышев В.П., Левицкая С.А., Филиппова Л.М. Аналитическая химия ртути. М.: Наука, 1974. 231 с.
14. Shen F., He S., Li J., Liu C., Xiang K., Liu H. Formation of sulfur oxide groups by SO_2 and their roles in mercury adsorption on carbon-based materials. *Journal of Environmental Sciences*. 2022;(119):44—49.
https://doi.org/10.1016/j.jes.2021.11.011
15. Wadi V.S., Mittal H., Fosso-Kankeu E., Jena K.K., Alhassan S.M. Mercury removal by porous sulfur copolymers: Adsorption isotherm and kinetics studies. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2020;(606):125333.
http://dx.doi.org/10.1016/j.colsurfa.2020.125333
16. Lennie A.R., Charnock J.M., Pattrick R.A.D. Structure of mercury (II)—sulfur complexes by EXAFS spectroscopic measurements. *Chemical Geology*. 2003;199(3-4):199—207.
https://doi:10.1016/S0009-2541(03)00118-9
17. Bell A.M.T., Charnock J.M., Helz G.R., Lennie A.R., Livens F.R., Mosselmas J.F.W., Pattrick R.A.D., Vaughan D.J. Evidence for dissolved polymeric mercury (II)—sulfur complexes. *Chemical Geology*. 2007;243(1-2):122—127.
https://doi.org/10.1016/J.CHEMGEO.2007.05.013
18. Al-Jibori S.A., Al-Doori L.A., Al-Janabi A.S.M., Alheety M.A., Wagner C., Karadag A. Mercury (II) mixed ligand complexes of phosphines or amines with 2-cyanoamino thiophenolate ligands formed via monodeprotonation and carbon—sulfur bond cleavage of 2-aminobenzothiazole. *X*-ray crystal structures of $[Hg(SC_6H_4NCN)(PPh_3)]_2$ and $[Hg(SC_6H_4NCN)(Ph_2PCH_2PPh_2)]_2$. *Polyhedron*. 2021;(206):115349.
http://dx.doi.org/10.1016/j.poly.2021.115349
19. Shunin V.A., Sokolova I.S., Lebed A.B. Sorption purification of productive selenium solutions from heavy metal impurities. In: *New technologies for the enrichment and complex processing of difficult-to-enrich natural and man-made mineral raw materials (Plaksin readings 2011)*: Abstracts of the reports of the International Meeting (Verkhnyaya Pyshma, 19–24 September 2011). Ekaterinburg: Fort Dialog-Iset, 2011. P. 428–429. (In Russ.).

Шунин В.А., Соколова И.С., Лебедь А.Б. Сорбционная очистка продуктивных селеновых растворов от примесей тяжелых металлов. В сб.: *Новые технологии обогащения и комплексной переработки труднообогатимого природного и техногенного минерального сырья (Плаксинские чтения 2011):* Тезисы докладов международного совещания (Верхняя Пышма, 19—24 сент. 2011 г.). Екатеринбург: Форт Диалог-Исеть, 2011. С. 428—429.

20. Habashi F. Metallurgical plants: How mercury pollution is abated. *Environmental Science and Technology*. 1978; 23(13):1372—1376. https://doi.org/10.1021/ES60148A011
21. Hylander I.D., Herbert R.B. Global emission and production of mercury during the pyrometallurgical extraction of nonferrous sulfide ores. *Environmental Science and Technology*. 2008;42(16):5971—5977. https://doi.org/10.1021/es800495g
22. Yu M-H., Yang H-H., Gu Y-C., Wang B-H., Liu F-C., Lin I.J.B., Lee G-H. Formation of anionic NHC complexes through the reaction of benzimidazoles with mercury chloride. Subsequent protonation and transmetallation reactions. *Journal of Organometallic Chemistry*. 2019;(887):12—17. https://doi.org/10.1016/J.JORGANCHEM.2019.02.015
23. Tugashov K.I., Gribanyov D.A., Dolgushin F.M., Smol'yakov A.F., Peregudov A.S., Klemenkova Z.S., Matvienko O.V., Tikhonova I.A., Shur V.B. Coordination chemistry of anticrowns. Isolation of the chloride complex of the four-mercury anticrown $\{[(o,o'\text{-}C_6F_4C_6F_4Hg)_4]Cl\}^-$ from the reaction of o,o′-dilithiooctafluorobiphenyl with $HgCl_2$ and its transformations to the free anticrown and the complexes with o-xylene, acetonitrile, and acetone. *Organometallics*. 2017;36(13): 2437—2445. https://doi.org/10.1021/ACS.ORGANOMET.7B00315
24. Al-Amri A-H.D., Fettouhi M., Wazeer M.I.M., Isab A.A. Synthesis, *X*-ray structure and ^{199}Hg, ^{77}Se CP MAS NMR studies on the first tris(imidazolidine-2-selone) mercury complex: {chloro-tris[N-methyl-2(3H)-imidazolidine-2-selone]mercury(II)}chloride. *Inorganic Chemistry Communications*. 2005;8(12):1109—1112. https://doi.org/10.1016/J.INOCHE.2005.09.010
25. Hadjikakou S.K., Kubicki M. Synthesis, characterisation and study of mercury (II) chloride complexes with triphenylphosphine and heterocyclic thiones. The crystal structures of [(benzothiazole-2-thionato)(benzothiazole-2-thione)(bis-triphenylphosphine) chloro mercury (II)] and [(μ_2-dichloro){(bis-pyrimidine-2-thionato)mercury (II)}{(bis-triphenylphosphine) mercury (II)}] at 100 K. *Polyhedron*. 2000;19(20-21):2231—2236. https://doi.org/10.1016/S0277-5387(00)00533-7
26. Pazderski L., Szlyk E., Wojtczak A., Kozerski L., Sitkowski J., Kamieński B. The crystal and molecular structures of catena[bis(μ_2-chloro)-(μ_2-pyridazine-N,N′)] cadmium (II) and catena[bis(μ_2-chloro)-(μ_2-pyridazine-N,N′)]mercury (II) and the solid-phase ^{13}C, ^{15}N NMR studies of Zn(II), Cd(II), Hg(II) chloride complexes with pyridazine. *Journal of Molecular Structure*. 2004;697(1-3): 143—149. https://doi.org/10.1016/j.molstruc.2004.03.048
27. Korolev A.A., Shunin V.A., Timofeev K.L., Maltsev G.I., Voinkov R.S. Sorption purification of selenic acid solutions from mercury. *Chemistry for Sustainable Development*. 2022;(4):372—382. (In Russ.). http://doi.org/10.15372/CSD2022393
    Королев А.А., Шунин В.А., Тимофеев К.Л., Мальцев Г.И., Воинков Р.С. Сорбционная очистка от ртути растворов селенистой кислоты. *Химия в интересах устойчивого развития*. 2022;(30):372—382.

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