Chemical Industry & Chemical Engineering Quarterly

Available online at
Association of the Chemical Engineers of Serbia *AChE*
www.ache.org.rs/CICEQ

Chem. Ind. Chem. Eng. Q. 29 (3) 169–178 (2023) CI&CEQ

PAVEL SHCHERBAN[1]
ALEXANDER GAPCHICH[2]
ALEKSEY ZHDANOV[3]
OLGA LETUNOVSKAYA[4]

[1]I. Kant BFU, Engineering and Technical Institute, Kaliningrad, Russia

[2]ICEMR RAS, Institute of Comprehensive Exploitation of Mineral Resources Russian Academy of Sciences, Moscow, Russia

[3]RSGU named after Sergo Ordzhonikidze, Moscow, Russia

[4]Saint Petersburg Mining University, St. Petersburg, Russia

SCIENTIFIC PAPER

UDC 622:66:54

OPTIMIZATION OF EXCESS BRINES DISPOSAL METHODS AT POTASH MINING AND PROCESSING PLANTS

Article Highlights

- Problem of optimization of potash ores processing
- Preparation and utilization of excess brines
- Backfilling of excess brines, implementation of technology
- Combining different utilization technologies
- Economic and organizational aspects of excess brine utilization

Abstract

The paper analyzes the positive and negative aspects of various technological solutions for the liquid brines used during the development of polymineral potash ore deposits and considers the problem of determining the choice of the optimal approach by considering geological, technical, environmental, and financial factors. The study of the issues of utilization and reduction of the liquid brines components of discharges in the production of potash fertilizers, the simultaneous reduction of valuable components loss with liquid discharges, and, due to this, increasing the production of potash fertilizers, and the usage in the technology of mine brines, are an urgent and important scientific and engineering challenge of the potash industry. Technologically, several alternative solutions can reduce the number of liquid by-products placed in sludge storage. The work used analytical methods, including statistical data processing, modeling, pre-design studies of technological solutions, and assessment of economic costs. Excess brines of potash mining and processing plants are liquid waste obtained during the production of potash fertilizers - MOP и SOP. The accumulation of excess brines in sludge storage facilities is estimated at millions of cubic meters per year. However, the expansion of the sludge storage facilities area and the construction of dams are only temporary solutions. They are associated with risks in the design, construction, and operation of hydraulic structures, increasing the risks of brine leakage into open and underground water basins. Therefore, it makes it necessary to use other methods of brine disposal. Depending on the nature of the processed polymineral potash ores, several methods can be combined to dispose of excess brines at once: backfilling, osmosis, injection into deep horizons, and multistage evaporation. The most optimal combination of brine reduction technologies for potassium-magnesium processing plant's raw materials is the following: 60% is disposed of by usage of vacuum evaporation units, 20 % by injecting excessive brines into deep absorbing horizons, and 10%–20% should be used for backfilling or additional products production.

Keywords: backfilling, cogeneration, excess brines, potash ore processing, vacuum evaporation.

Among the main industrial methods of excess brines disposal, the following can be distinguished: vacuum-evaporation of brines with subsequent salt, crystallization, injection into deep absorbing horizons (IIDAH), backfilling of exhausted space in the mine (hydro-backfilling, hardening backfilling) [1]. Also, in some cases and technological processes, reverse osmosis and thermohydrolysis of bischofite liquor with the magnesium oxide and hydrochloric acid productions are. The content of the main technologies

---

Correspondence: P.Shcherban, Immanuel Kant Baltic Federal University, Engineering and Technical Institute, Kaliningrad, 57 Ozerova St.236006, Russia.
E-mail: ursa-maior@yandex.ru
Paper received: 28 December, 2021
Paper revised: 16 June, 2022
Paper accepted: 1 September, 2022

https://doi.org/10.2298/CICEQ211228024S

that solve potash production by-product placement will be briefly explained.

Thus, the excess brine evaporation is carried out in a multiple-effect evaporation system. Evaporators consist of a heating chamber, in the center of which there is a boiling pipe and a separator. This device separates the solution steam from the boiling solution [2]. The circulation of the evaporated solution through the heating chamber tubes is carried out using a pump; the heating steam enters the inter-tube space. The solution is heated in the heating chamber tubes to a temperature exceeding the boiling point; boiling the solution occurs in the boiling pipe above the heating chamber. The evaporated solution and the crystallizing solid phase are removed from the separator's lower part. Considering the accumulation of atmospheric precipitation and other production factors in brine storage facilities, the brines with a low-temperature depression make it technically possible to use vacuum evaporation units with a heat pump.

On the other hand, backfilling technology is a hydraulic transport or hardening mixture transport system of the processing plant wastes into the exhausted space of the mine. Thus, these by-products are placed in the exhausted spaces of the mine, reducing the areas alienated for placing these volumes on the surface and reducing the environmental load on the area near the production. Besides, in the case of the hardening backfilling mixture usage (i.e., material gaining the strength comparable to the surrounding mining massif), it's possible to increase the extraction of useful components without significantly disrupting the geomechanical stability of the overlying layers [3].

Excess brine pumping technologies are based on returning raw oil water and are currently a fairly well-developed method. The main requirements are the maximum compliance of the chemical water composition with the initial composition of the fluid. In addition, it is preferable to observe the temperature regime to prevent increased salt deposition on the equipment and in the bottom-hole zone of the well. As for potash plants, deciding on injection requires a fairly detailed, costly, and time-consuming study, which includes: the search for a suitable reservoir formation, the justification of the reservoir closure and its tightness, reservoir protection from tectonic and other geological factors, the study of the reservoir capacitance properties, investigation of pressure parameters, permeability and effective porosity of rocks, the material composition of the reservoir, its inertia in relation to the injected brines. Therefore, a mandatory stage is full-scale tests on pilot wells for 1.5 to 2 years (the analysis of seasonal change influence), which allows us to obtain specific parameters of the good pick-up rate and to perform calculations of the injection complex. The minimum number of wells can be defined as - working, observation/backup, and monitoring [4].

An additional way of brine utilization is membrane technologies. Many foreign and domestic publications, both fundamental and applied, are devoted to describing membrane technologies [5], describing in detail the nuances of the membrane behavior in various processes.

The membrane is a porous partition having pores similar in size. During the filtration process, particles with sizes larger than the pore size are retained. In contrast, the filtrate (permeate) containing smaller particles, including solvent molecules, can pass through the pores [6].

According to this approach, the following division of membrane technologies has historically been established based on the size and nature of the separated impurities. Microfiltration detains particles larger than 0.1 μm–1 μm (large colloids, suspensions, bacteria). The working pressure is usually up to 1 atm–2 atm. Ultrafiltration separates much smaller particles - in the range of 0.01 μm–0.1 μm, including colloids and large organic molecules that are retained (with a molecular weight of over 1000 Da). Nanofiltration effectively detains components of substances with a size of 0.001 μm–0.01 μm, an organic matter with a molecular weight starting from 500 Da. The working pressure of the process is from 3 atm to 20 atm. Nanofiltration removes chromaticity, organic matter, pesticides, hardness salts, and microbiological contamination. Reverse osmosis removes dissolved salts (filtration rating at 0.0001 μm–0.001 μm) and organic matter (with a molecular weight of less than 500 Da). The working pressure is up to 150 atm.

Despite the apparent simplicity of membrane processes, their practical use became possible only after developing the necessary materials, membrane manufacturing technologies, special pumps and valves, automation systems, etc.

All membranes for nanofiltration, reverse osmosis, and most micro- and ultrafiltration membranes are made of organic polymers. Porous membranes are used for micro- and ultrafiltration, and non-porous membranes are used for nanofiltration and reverse osmosis. The main advantage of polymer membranes is high processability and great possibilities for controlling the properties and structure of the membrane by small chemical and/or technological variations of the manufacturing process.

Achieving acceptable performance with low membrane permeability requires using elements with a high specific membrane area per unit volume of the apparatus. These can include semi- fiber and roll elements (Fig. 1).

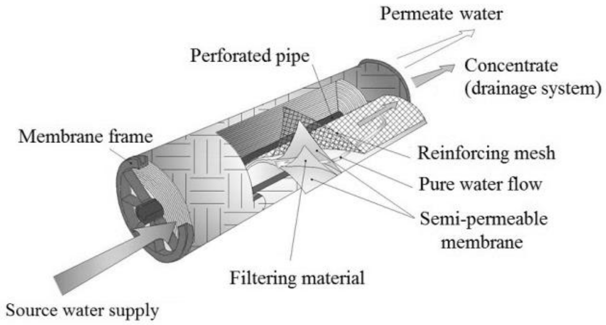

Figure 1. Structure of the nanofiltration roll element.

Special attention should be paid to the works of scientists [7], which describe promising technologies for the utilization of brines using a stimulating membrane [membrane-promoted crystallization (MPC)]. The resulting "needle-like" KCl crystals have a relatively small contact area with the membrane, which ensures easy removal of KCl from the membrane surface for its regeneration and further use. The MPC process demonstrates high KCl performance (up to 134.3 g/m^2). The MPC process provides a new and promising approach to the sustainable production of KCl from KCl brine; thereby, in addition to the problem of brine utilization, the task of increasing the KCl extraction and reducing irretrievable losses of a valuable component with waste is solved, which determines the integrated use of mineral raw materials.

Nanofiltration and reverse osmosis membranes impose stricter requirements on the quality of the treated medium. Usually, a preliminary cleaning is required, which removes suspended particles, dissolved iron, aluminum, and manganese and neutralizes oxidants [7]. During operation, a large amount of dirt gradually accumulates on the surface and in the membrane's pores. This sediment reduces the productivity of the equipment. The equipment operation can be improved by conducting a membrane regeneration cycle. Despite the industrial type of such equipment, reverse osmosis has not found a wide practical application in potash plants.

Problems of technological process optimization

Next, we will analyze several materials on the excess brine disposal methods at enterprises that enrich potassium-magnesium ores for the effectiveness of their use in the disposal of excess brines. Recent studies show a particular prospect of modernization of flotation technology during ore enrichment (including polymineral ones) that reduces the concentration and volume of by-product brines remaining after production [8]. At the same time, along with the search for a new reagent that provides a more efficient flotation process, the search for reducing the operating costs of evaporation equipment is continuing since this would also reduce the volume of excess brines obtained in the main technological process[9]. In industrial practice, there are two main energy recovery: multiple-effect evaporator systems and heating compressors [10,11].

Multiple Effect Evaporation (MEE). The energy balance of a single-step evaporation unit indicates that the heat content of the secondary steam is approximately equal to the heat supplied from the heating side of the heat exchanger. If the secondary steam under the action of the primary energy source (steam from the boiler facility) is used as a heating element in the second step of the unit, the energy consumption will be reduced by approximately 50%. The same principle can be used in subsequent steps and, thus, saves thermal energy. The maximum heating temperature at the first stage and the lowest boiling point at the last stage form a common temperature difference distributed across all the stages in the device. Accordingly, the temperature difference in each step decreases with an increased number of steps.

The minimum temperature difference between the multiple-effect evaporation unit is determined by the sum of the temperature difference required for effective heat transfer from the heating steam to the evaporated medium (6 °C–11 °C) and the temperature difference at the boiling point of the brine and the solvent (temperature depression). Due to the distribution of the total temperature difference between the boilers into several ones, it becomes necessary to increase the heating surface of each boiler to ensure the required performance for evaporated water at a smaller temperature difference. During the first approximation, it can be assumed that the area of the heat exchange surfaces in all boilers increases in proportion to the number of boilers. Consequently, the capital cost of the installation increases linearly, while the increase in energy efficiency during the transition to each subsequent boiler increases at a slower rate. The main advantage of MEE is the repeated use of the heat content of the primary heating steam. However, these units are characterized by significant disadvantages: high cost and significant dimensions of the units, which occupy a significant part of the industrial area (Fig. 2) [12].

Mechanical vapor recompression (MVR). Iterative use of the heat of the primary heating steam can be achieved in a single-stage unit at any desired boiling point of the solution by applying mechanical vapor recompression (MVR). The evaporation unit with MVR operates based on the principle of the Carnot cycle of a high-speed centrifugal compressor, in which the secondary steam is partially or wholly sucked in by a steam jet injector or a turbocharger and recompressed

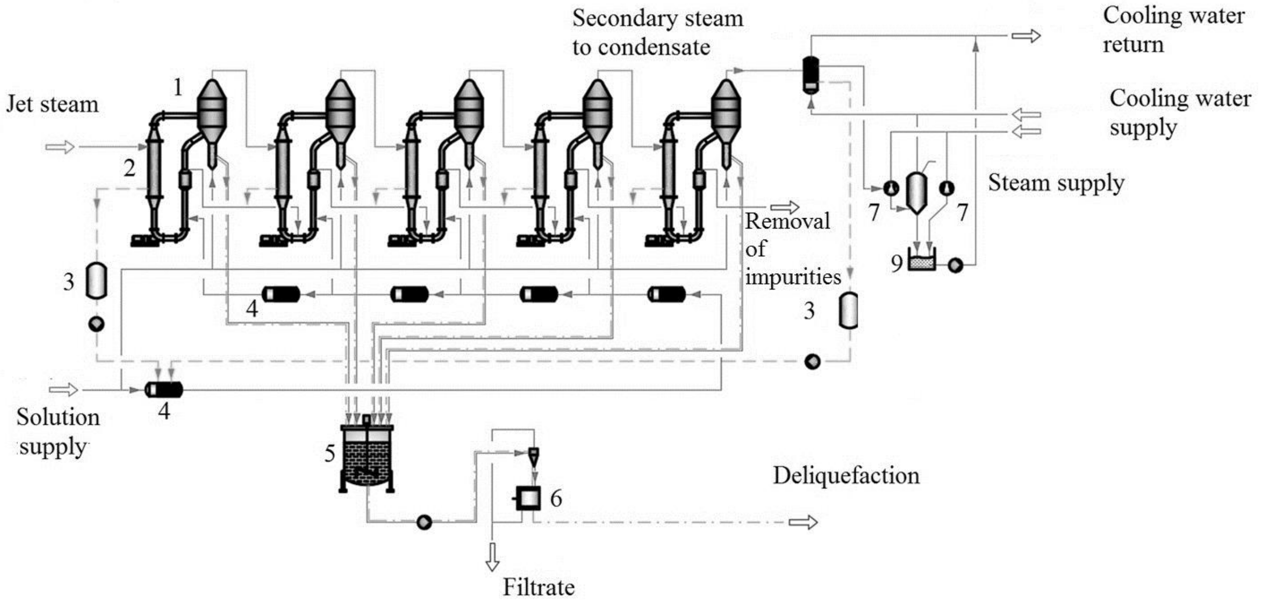

Figure 2. Multiple Effect Evaporation (MEE): 1 - Vacuum Crystallization Unit (VCU); 2 - Heat Exchanger unit; 3 - Process Condensate Tank ; 4 - Heater; 5 - Agitation Tank; 6 - Centrifuge; 7 - Steam ejector; 8 - Condenser; 9 - Hotwell.

to the level of a defined heating steam pressure. Then, this stream is used to heat the same unit. The energy of vaporization is generated due to an isentropic increase in the steam enthalpy. Secondary steam condensate is also used to heat brine to a preset incoming temperature. Due to such intensive heat recovery, the consumption of additional heating steam is not required in most cases, except for steam ejectors in the final step (Fig.3) [13]. The steam consumption for steam ejectors is insignificant and amounts to (2–3) tons per hour.

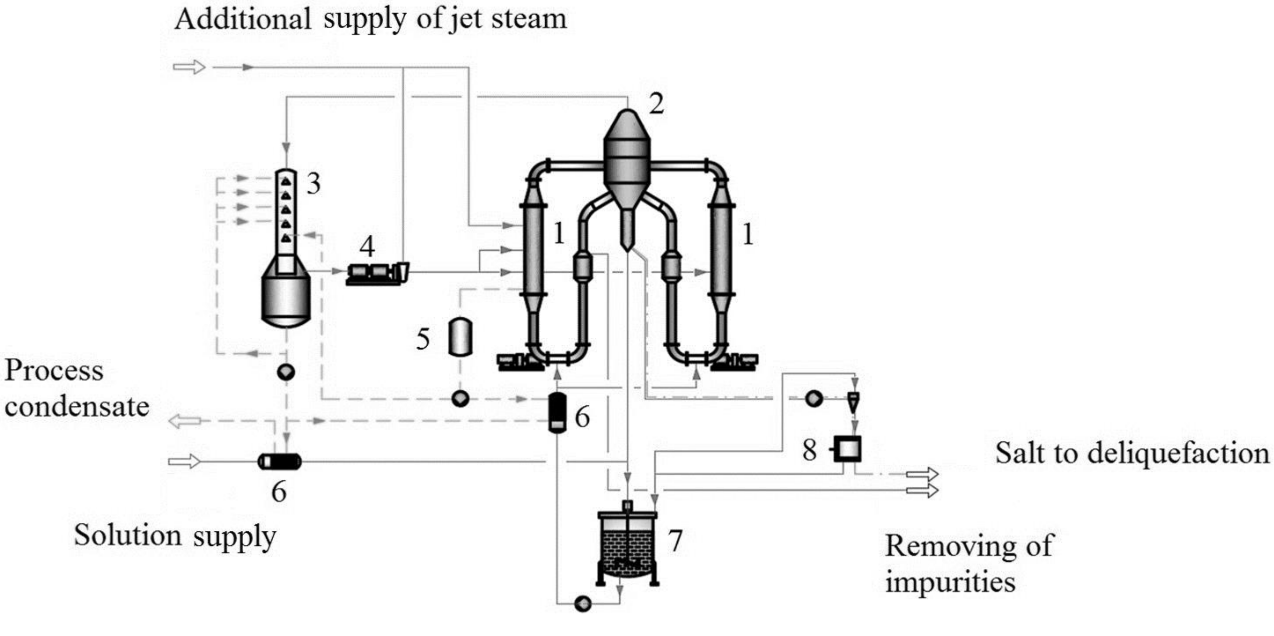

Figure 3. Mechanical Vapor Recompression: 1 - Heat Exchanger; 2 - Evaporative Crystallizer; 3 - Scrubber; 4 - Compressor; 5 - Condensate collector; 6 - Heater; 7- Equalizing Tank; 8 - Centrifuge.

The advantage of MVR is the possibility of repeated use of secondary heating steam in a closed cycle, which allows evaporation to be carried out in a single-stage boiler, thereby reducing the metal consumption of the equipment and operating costs. Nevertheless, the volume of investment in capital expenses during the installation of compresses increases by 20%–30%. In addition, the energy consumption of the vacuum evaporation unit with MVR increases significantly.

Thus, one compressor has 4.2 MW–6.3 MW of installed capacity. The practice of Greenfield projects approves the number of investments for MVR capital expenditures that can be paid back within 5 years to 6 years, depending on electricity tariffs in a particular region [14]. Table 1 shows a comparative analysis of the energy consumption and MVR unit based on the calculation at the designed plant for the disposal of excess brines with a capacity of 1 million m^3 per year, located in the Perm Region of the Russian Federation. Energy costs in this region are estimated at 0.016 US dollars per Giga calories for steam heating and 0.035 US dollar per kilowatt.

Table 1. Technical characteristics and cost of MEE and MVR for the disposal of 1 million cubic meters of brines per year.

OPEX	MEE	MVR
Heating steam consumption from the boiler room, t/h	230	11
Installation capacity, kW	3 500	27 100
Cooling water consumption, m^3/h	6500	850
Specific cost of steam, rub/kg	0,6	0,6
Specific cost of electricity, rub/kWh	2,43	2,43
Working Time Fund, hours/year	8000	8000
Steam cost (per year), million rubles	1 104	53
The cost of electricity (per year), million rubles	64,04	526,82
Total, rub	1 172 040 000	579 620 000
Total, Euro	15 026 154	7 431 077

MVR saves the consumption of conventional fuel, which can be converted to natural gas or fuel oil, for generating heating steam about 20 times, which causes a significant reduction in greenhouse gas CO_2 emissions, thereby reducing the need for a quota for CO_2 emissions into the atmosphere. This factor is gaining relevance yearly, considering the agreement under the UN Framework Convention on Climate Change (the Paris Agreement). It is important to note that in the above OPEX calculation, it is necessary to clarify the tariffs for energy resources in a particular region.

Fluctuations in the cost of steam production may differ by 10%–15%. In this case, the calculation mentioned above shows a decrease in OPEX for MVR in the amount of 8-10 million euros per year, and the return on investment of CAPEX for MVR is reduced to 5 years. However, this calculation does not consider the specific costs of producing cooling water from cooling towers, which is 7.6 times higher at MEE compared to MVR, and does not consider the costs of CO_2 emission quotas into the atmosphere [15]. If these costs are considered, the investment return period will be reduced from 5 years to 4 years.

It is reasonable to consider cogeneration by installing a turbine in a boiler room to reduce the purchase of electricity. Electricity is generated as a co-product in the cogeneration cycle using a turbine. As a result, additional electrical energy is generated from each normal cubic meter of natural gas with a total heat utilization coefficient of 82%–95%. In steam turbine installations, its share is about 28%–39%, in gas turbine installations was 30%–37%, in gas piston installations was 38%–48%, and in combined-cycle gas installations was 53%–62%. Therefore, CAPEX and OPEX should be considered when developing a feasibility study of technical solutions. International experience shows that electric energy costs 2.5 to 6 times greater than thermal energy. It is greater by 4 to 6 times in the central part of the Russian Federation, while in other regions of the Russian Federation is up to 6 to 7 times. That is why it is worth considering the operating costs of greenfield projects cogeneration. So, if one unit of heat costs one standard unit, then one unit of electricity will cost four standard units. Given that the efficiency of modern boilers reaches up to 95%, it can generate income in the amount of 95 standard units. Therefore, the formula of one installation will determine the total cost of generated energy resources:

$$F = F_{el} + F_{th.en}\left[stand.\ unit\right] \tag{1}$$

Thus, it is possible to estimate cogeneration units' cost and economic potential. If we consider an installation with one boiler and four turbines, we'll get the following: In a steam turbine (ST), an average of 34 units of electric energy and 53 units of thermal energy are obtained, then;

$$F_{st} = 34 \times 4 + 53 \times 1 = 189\ standart\ units\ (\$) \tag{2}$$

For a gas turbine (GT), this indicator will be:

$$F_{gt} = 33 \times 4 + 52 \times 1 = 184\ standart\ units\ (\$) \tag{3}$$

For gas piston (GPT), this indicator will be:

$$F_{gpt} = 43 \times 4 + 46 \times 1 = 218\ standard\ units\ (\$) \tag{4}$$

For combined-cycle gas (CCG):

$$F_{ccg} = 55 \times 4 + 33 \times 1 = 253\ standard\ units\ (\$) \tag{5}$$

Concerning a conventional boiler facility, the economic effect will reach 199%, 194%, 229%, and 266%, accordingly. Thus, the technical solution for cogeneration in the process of brine evaporation is, on average, 200%–270% more profitable than using a boiler facility.

The disposal of exhausted gases from a combined heat and power plant should be considered with an absorption refrigeration unit (trigeneration) for colling water production. The cogeneration-trigeneration cycle allows the use of resource-saving technologies and makes potash production energetically effective and should be one of the subjects of detailed analysis at the Pre-FEED and FEED stages. To develop optimal technology and make rational technical decisions on the disposal of excess brines, it is necessary to carry out a consistent study and analysis of technological solutions, infrastructure, and environmental risks at all project stages. For example, at the Pre-FEED stage, it is necessary to conceptually work out all possible industrial disposal methods with the determination of recycling volumes, feasibility studies of technical solutions, and environmental aspects.

Further development of the project will require implementing an integrated technical and economic assessment (PEA) with the introduction of additional factors - analysis of CO_2 emissions and social risks [15].

Problems of applying excess brine subsoil injection technology

In general, considering the global trends in the upgrading of industrial plants to "green production" and the implementation of such tools as carbon taxes and quota trading systems (STC, emissions trading system, ETS), the authors believe that it is reasonable to consider a combined approach with a ranking of the entire volume of processed brines [16]. For example, a possible solution for the disposal of excess brines from large brine storage facilities (with a volume of more than 3 million m^3 per year) is a simultaneous use of an evaporation unit to obtain technical salt and unit of excess brines injection with a ratio of 60% to 40%. This proportion is determined by absorbing horizons and their porosity, as well as by a comparative analysis of the capital costs of evaporation and excess brine injection. Nowadays, the regulatory framework justifying the use of excess brines injection technology in Russia is in the formation process [17]. For example, the document regulating the procedure for considering applications for obtaining the right to use subsurface resources for placing liquid waste generated by mining enterprises engaged in exploration and production, as well as primary processing of potassium and magnesium salts in rock formations, was adopted only in November 2019.

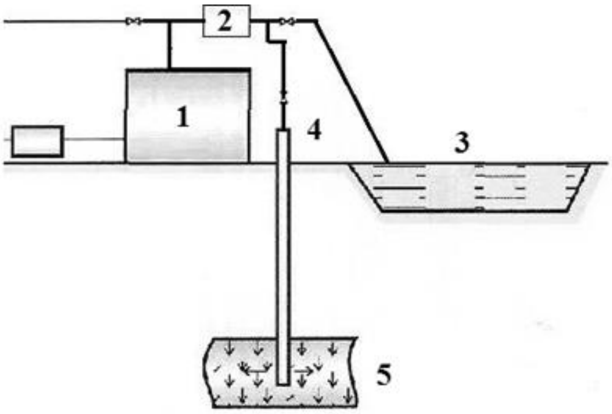

Figure 4. Enlarged system of excess brine disposal: 1 - Storage tanks for the accumulation of by-products at the processing plant; 2 - Pumping fleet; 3 - Surface brine storage; 4 - Injection well system; 5 - Receiving subsoil layer.

The sequence of work is not clearly structured because to apply for a geological study (in Greenfield form), "the conclusion of the state expert examination of geological information on the subsurface area" should be provided, and "information regarding the subsurface area planned for construction, as well as water generated by subsurface users, engaged in exploration and production, and primary processing of potassium and magnesium salts" is also required. In addition, the subsurface user must perform a pre-project study (including a seismic survey of the territory and drilling wells with collecting information about reservoirs) [18].

Further, after obtaining a license, developing a geological exploration project following the requirements is necessary. At the same time, it should be noted that nowadays, there are requirements for reservoir waters in Russia's oil and gas industry, and there are no special requirements for excess brine production.

The problem of environmental assessment with these approaches remains open - whether the geological exploration project is the object of such an examination [19]. Further, after passing the examination of geological information, it is required to develop a project of a complex for pumping. Thus, the issue of assessing the economic efficiency of the injection complex should be solved by the subsurface user already at the initial stage - since the implementation of the entire complex of studies will require large capital expenditures in the absence of a sufficient amount of information. Figure 4 shows an enlarged scheme of pumping excess brines into absorbing horizons. It follows from the above that it is possible to speak about the prospects of studying excess brine injection with a certain degree of confidence if the following factors are observed, in order of their significance:

1. The presence of a detailed geological study of the potash plant area by geophysical methods and the presence of geotectonic schemes;
2. The location of the potash plant in the oil/gas producing region or potentially oil and gas bearing region where the study of reservoirs was carried out.
3. Detailed study of infrastructure and environmental risks.

When analyzing environmental risks and preparing an environmental monitoring program, it is mandatory to use remote and high-precision methods for monitoring neotectonic movements and processes on the Earth's surface, which will allow to not only prevent risks related to the operation of the complex on time but also to level up the impact on the subsurface and the environment.

Problems of backfilling technology implementation

The existing technologies of backfilling waste have several features, especially in mining enterprises. Firstly, the limiting factor could be the volume of free subsurface space. As a result, the work schedule on the deposit becomes critical for waste backfilling [20]. The second limiting factor is the geomechanical stability of the filled chambers. Therefore, before carrying out the laying measures, it is necessary to determine the minimum required strength, which the laying mass should gain over time. Based on this, the management of the enterprise decides on the use of binding components in the backfilling mixture. Finally, the devices that are part of the backfilling pipelines and the pipes themselves are subjected to a complex hydroabrasive effect of the flow; this is primarily due to the peculiarities of their functioning, changes in the parameters of the conducted (pumped) medium, the specifics of the geometry of the joints, and has many limitations of either technical or natural and economic nature. Indeed, the operation of such systems and the maintenance of their operable condition and reliability generally are non-trivial problems [21].

It is important to consider the current processes and factors arising during the operation phase itself and the parameters that form its technical and technological characteristics when speaking about the reliability of pipelines as a system operating under conditions of waterjet wear. Thus, at the stage of pipeline design, the subsequent operational reliability is influenced by the rationality of design decisions (the sequence of system elements and their correspondence to each other and technological parameters), the choice of materials and components, and the choice of operating modes [22]. As a result, the backfilling method is a complex task faced by subsoil users. It requires a unified order of steps and investigations, considering all the abovementioned problems (Fig.5).

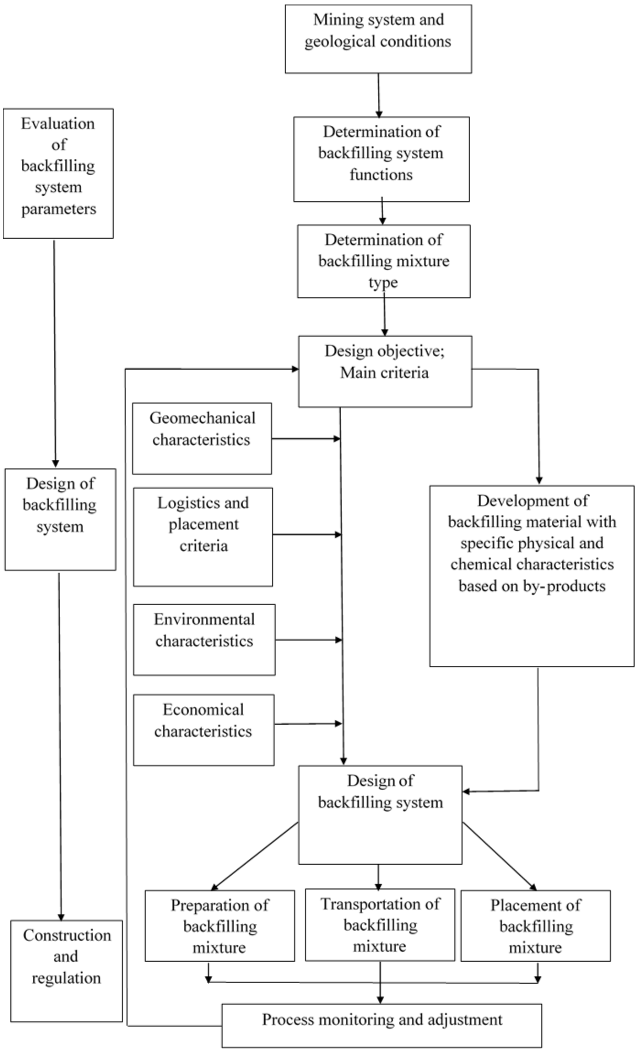

Figure 5. The procedure of development and implementation of a backfilling system at the processing of polymineral salts.

Thus, the use of each of the methods of polymineral production of by-products has several limitations, either technical, natural, or economic. In addition, it leads to the necessity of different method combinations to ensure both production volumes and environmental safety.

Combining disposal technologies in the extraction and processing of potash ores

A whole range of factors should be considered when investigating the optimization of technological choices for excess brine disposal at potash plants. Thus, the efficiency of the useful component recovery from spent liquor, the problem of maintaining the environmental safety of production, and ensuring the stability of the mountain massif with a hardening backfilling are not the only ones of great importance, but also the economic costs of implementing these measures [23].

First, it should be mentioned that the costs for each designated scheme can be capital and variable.

For example, capital expenditures may include the creation of a surface-laying complex, installing a cogeneration and trigeneration system at plants, purchasing a license to pump into deep horizons, etc. (Figure 6).

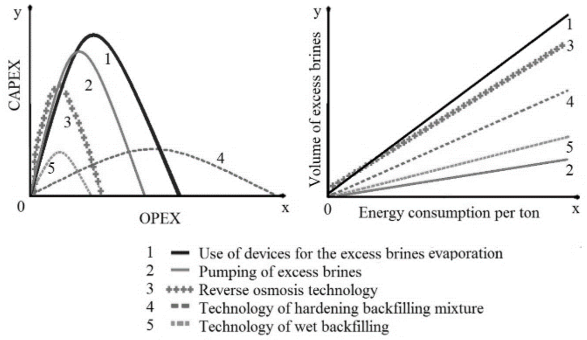

Figure 6. Generalized dependencies and modeling results typical for Eastern Europe: a - the volume of capital and operating costs by use of various technologies for the disposal of excess brines; b - the volume of disposal of excess brines from energy consumption per ton of the disposed of substance 1 - the use of devices for the evaporation of excess brines; 2 - the injection of excess brines; 3-reverse osmosis technology; 4 - the technology of hardening reverse backfilling; 5 - the technology of hydro-backfilling.

Variable costs include the purchase of additional reagents and binders, consumables, and tax and fee payments. In part, these costs can be compensated by the additional product volumes for sale or by reducing deductions for unrealized by-products (rational use of subsurface resources).

Therefore, from a mathematical point of view, the problem under consideration can be represented as a series of functional dependencies (Fig. 6). On the one hand, the search for the minimum area value from the functions (in a simplified scheme, this is a two-dimensional model, the resulting of which is capital and operating costs for technological processes), and on the other hand, as the most effective volume ratio of recyclable material to energy costs [24].

As a result, a system of equations will be obtained. Its solution $R = (S_n, F_n)$ will allow us to find the optimal ratio of the technologies used to dispose of excess brines in specific project conditions [25]. It should be noted that in both equations, the minimum value of indicators will be optimal (both in terms of capital and current costs for the lye disposal (S_{opt}) and in terms of energy consumption per 1 ton of recycled lye (F_{opt})).

$$R = \left\{ \begin{array}{l} S_{opt} \to \min = \dfrac{\partial S}{\partial S_n};\ where\ S_n = \int_0^2 ax - x^2 dx; \\ Fopt \to \min = \dfrac{\partial F}{\partial F_n};\ where\ \mathrm{F}_n = \dfrac{1}{2} ab \end{array} \right\} \tag{6}$$

CONCLUSION

Indeed, there may be one technological solution for disposing of excess liquor/lye at the plant, which will be determined by the method described above. However, as a rule, the company solves not only the tasks of minimizing financial costs for disposal but also several technical and technological tasks (ensuring the geomechanical stability of the minefield, ensuring the environmental friendliness of disposal processes, rational development of the subsoil) [26].

These factors can significantly influence the choice of a particular technology for excess lye disposal. As a rule, several technologies can be used simultaneously at the plant for various reasons.

Geoecological security and stability of the territory development where such production is located require comprehensive studies on the possibility of using above mentioned methods. Sustainable development of the region adjacent to the enterprise with extraction and processing of polymineral raw materials will be possible only if the possibilities and safety of the natural environment for the by-products acceptance will be considered and accepted as the priority goal.

Modeling shows that for enterprises producing potash fertilizers based on mine extraction, the most optimal combination of technologies in terms of excess liquor disposal volume is: 60% disposed of by using vacuum evaporation plants while obtaining additional products, 20% by pumping excess brines through wells, 10%–20% by backfilling or membrane technologies with the additional recovery of potash salts. This ratio is obtained based on the result analysis of technical and economic calculations and practical experience of mining enterprises (the technological processes of enrichment used for the Khartsals of the Central European Tsekhstein salt basin are taken as the basis of modeling). A detailed description of the mathematical model that determines the cost and efficiency ratio of various by-product brine disposal methods is not given since it is company know-how and is currently undergoing the patenting procedure. At the same time, for various polymineral ores, such a model can be significantly changed (an important role is played not only by the physicochemical characteristics of the initial ore and the final products obtained but also by energy costs, capital investments, and environmental charges, which vary from country to country). The above calculations and modeling results will be closest to the conditions of Poland, Russia, Belarus, and Ukraine. The structure of the model will undergo much greater changes if the calculations are transferred to the examples of Germany and the UK (due to the changed energy and environmental costs) and significantly greater when applied to deposits in Canada or Australia. The final decision on the brine disposal or a combination of various technical solutions is made at the technical and economic assessment (PEA), considering all technical, geological, economic, and environmental aspects, including potential CO_2 emissions. It is worth pointing out that the evaporation of lye by the MEE method is a direct source of CO_2 due to the significant consumption of coolant (steam). Therefore, it is promising to consider evaporation by the MVR method with the recycling of coolant, which can reduce steam consumption and make the technology resource-saving.

The life cycle of technologies for excess brine disposal is determined at the detailed engineering stage of evaporation and crystallization plants or filtration membranes. Therefore, it must correspond to the entire life cycle of the mining enterprise. The life cycle of IIDAH is determined based on the presence of underground reservoirs and the pick-up of injection wells and is limited by these factors.

REFERENCES

[1] N. Afrasiabi, E. Shahbazali, Desalin. Water Treat. 35 (2011) 39–53. https://doi.org/10.5004/dwt.2011.3128.

[2] L. Shengo, Water, Air, Soil Pollut. 232 (2021) 273. https://doi.org/10.1007/s11270-021-05198-w.

[3] C. Bilibio, C. Schellert, S. Retz, O. Hensel, H. Schmeisky, D. Uteau, S. Peth, J. Environ. Manage. 196 (2017) 633–643. https://doi.org/10.1016/j.jenvman.2017.01.024.

[4] J. Shanxue, L. Yuening, P. Bradley, Sci. Total Environ. 59 (2017) 567–583. https://doi.org/10.1016/j.scitotenv.2017.03.235.

[5] S. Shenvi, A. Isloor, A. Ismail, Desalination 368 (2015) 10–26. https://doi.org/10.1016/j.desal.2014.12.042.

[6] C. Buckley, A. Simpson, C. Kerr, C. Schutte, Desalination 67 (1987) 431–438. https://doi.org/10.1016/0011-9164(87)90260-8.

[7] J. Guozhao, W. Wang, C. Huihuang, Y. Siyuan, J. Sun, W. Fu, B. Yang, Z. Huang, Desalination 521 (2022) 115389. https://doi.org/10.1016/j.desal.2021.115389.

[8] Z. Shiyong, Z. Huang, H. Wang, R. Liu, C. Cheng, S. Shuai, Y. Hu, Z. Guo, X. Yu, G. He, W. Fu, Int. J. Min. Sci. Technol. 31(6) (2021) 1145–1152. https://doi.org/10.1016/j.ijmst.2021.09.001.

[9] Z. Huang, S. Shuai, H. Wang, R. Liu, S. Zhang, C. Cheng, Y. Hu, X.Yu, G. He, W. Fu, Sep. Purif. Technol. Part B 282 (2022) 119122. https://doi.org/10.1016/j.seppur.2021.119122.

[10] Z. Huang, S. Zhang, F. Zhang, H. Wang, J. Zhou, X. Yu, R. Liu, C. Cheng, Z. Liu, Z. Guo, G. He, G. Ai, W. Fu, J. Mol. Liq. 313 (2020) 113506. https://doi.org/10.1016/j.molliq.2020.113506.

[11] M. Scott, Å. Jernqvist, J. Olsson, G. Aly, Appl. Therm. Eng. 19(3) (1999) 279–298. https://doi.org/10.1016/S1359-4311(98)00050-7.

[12] P. Donnellan, K.Cronin, E. Byrne, Renew. Sustain. Energy Rev. 42 (2015) 1290–1304. https://doi.org/10.1016/j.rser.2014.11.002.

[13] L. Urbanucci, D. Testi, Energy Convers. Manage. 200 (2019) 112062. https://doi.org/10.1016/j.enconman.2019.112062.

[14] B.R. Sridevi, P.A. Hoskeri, C.M. Joseph, Thin Solid Films 723 (2021) 138584. https://doi.org/10.1016/j.tsf.2021.138584.

[15] D. Dmitrieva, A. Ilinova, A. Kraslawski, Resour. Policy 52 (2017) 81–89. https://doi.org/10.1016/j.resourpol.2016.11.004.

[16] G.Wenzhong, Q. Jiaye, J. Zhang, C. Guangming, D. Wu, Int. J. Heat Mass Transfer 144 (2019) 118552. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118552.

[17] I. Chaikovskiy, O. Korotchenkova, D.Trapeznikov, Lithol. Miner. Resour. 54 (2019) 308–319. https://doi.org/10.1134/S0024490219040023.

[18] Q. Sun, J. Zhang, Q. Zhang, Environ. Earth Sci. 77 (2018) 234. https://doi.org/10.1007/s12665-018-7414-6.

[19] B. Deng, Z. Jia, W. Liu, X. Liu, J. Gu, W.Ye, H.Wen, Z. Qu. Energies 14(4) (2021) 791. https://doi.org/10.3390/en14040791.

[20] G. Ali, M. Fall, I. Alainachi. J. Mater. Civ. Eng. 33(3) (2021) 04020498. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003605.

[21] K. A. Hudson-Edwards, H. E. Jamieson, B. G. Lottermoser, Elements 7(6) (2011) 375–380. https://doi.org/10.2113/gselements.7.6.375.

[22] C.Wolkersdorfer, D.K.Nordstrom, R.D. Beckie, Mine Water Environ 39 (2020) 204–228. https://doi.org/10.1007/s10230-020-00666-x.

[23] M. Bortz, J. Burger, N. Asprion, S. Blagov, R. Böttcher, U. Nowak, A. Scheithauer, R. Welke, K.-H. Küfer, H. Hasse, Comput. Chem. Eng. 60 (2014) 354–363. https://doi.org/10.1016/j.compchemeng.2013.09.015.

[24] M.K.K. Nassar, R.M. El-Damak, A.H.M. Ghanem, Environ. Earth Sci. 54 (2008) 445–454. https://doi.org/10.1007/s00254-007-0849-9.

[25] S. P. Philbin, Res.-Technol. Manage. 51(2) (2008) 32–39. https://doi.org/10.1080/08956308.2008.11657493.

[26] M. S.Q. Domingues, L. Adelina, F. Baptista, M. Tato Diogo, Int. J. Min. Sci. Technol. 27 (4) (2017), 611–616. https://doi.org/10.1016/j.ijmst.2017.05.007.

PAVEL SHCHERBAN[1]
ALEXANDER GAPCHICH[2]
ALEKSEY ZHDANOV[3]
OLGA LETUNOVSKAYA[4]

[1]I. Kant BFU, Engineering and Technical Institute, Kaliningrad, Russia

[2]ICEMR RAS, Institute of Comprehensive Exploitation of Mineral Resources Russian Academy of Sciences, Moscow, Russia

[3]RSGU named after Sergo Ordzhonikidze, Moscow, Russia

[4]Saint Petersburg Mining University, St. Petersburg, Russia

NAUČNI RAD

OPTIMIZACIJA METODA ODLAGANJA VIŠKA SLANIH RASTVORA U RUDNIKU I POSTROJENJU ZA PRERADU POTAŠE

U radu se analiziraju pozitivni i negativni aspekti različitih tehnoloških rešenja za slane rastvore koji se koriste pri razvoju polimineralnih nalazišta rude potaše i razmatra problem određivanja izbora optimalnog pristupa uzimajući u obzir geološke, tehničke, ekološke i finansijske faktore. Proučavanje pitanja iskorišćavanja i smanjenja komponenti ispuštanja slanih rastvora u proizvodnji potašnih đubriva, istovremenog smanjenja gubitka vrednih komponenti sa tečnim ispustima, a zbog toga i povećanja proizvodnje potašnih đubriva, kao i upotreba u tehnologiji rudničkog slanog rastvora, hitan su i važan naučni i inženjerski izazov industrije potaše. Tehnološki, nekoliko alternativnih rešenja može smanjiti broj tečnih nusproizvoda u skladištu mulja. U radu su korišćene analitičke metode, uključujući statističku obradu podataka, modelovanje, predprojektne studije tehnoloških rešenja i procenu ekonomskih troškova. Višak slanih rastvora iz rudnika i postrojenja za preradu potaše je tečni otpad koji se dobija tokom proizvodnje kalijumovih đubriva. Akumulacija viška slanih rastvora u skladištima mulja procenjuje se na milione kubnih metara godišnje. Međutim, proširenje prostora za skladištenje mulja i izgradnja brana su samo privremena rešenja. Oni su povezani sa rizicima u projektovanju, izgradnji i radu hidrauličnih objekata, povećavajući rizik od curenja slane vode u otvorene i podzemne vode. Zbog toga je neophodno koristiti druge metode odlaganja slane vode. U zavisnosti od prirode prerađenih polimineralnih kalijumovih ruda, može se kombinovati nekoliko metoda za uklanjanje viška slanih rastvora : zatrpavanje, osmoza, ubrizgavanje u duboke slojeve i višestepeno isparavanje. Najoptimalnija kombinacija tehnologija redukcije slanog rastvora za postrojenje za preradu kalijumovih i magnezijumovih sirovina je sledeća: 60% se odlaže korišćenjem uređaja za vakuumsko isparavanje, 20% ubrizgavanjem viška rastvora soli u duboke slojeve, a 10%–20% treba koristi se za zatrpavanje ili proizvodnju dodatnih proizvoda.

Ključne reči: zatrpavanje, kogeneracija, višak slanih rastvora, prerada rude potaše, vakuumsko isparavanje.