SOME ASPECTS OF THE REVAMP OF EXISTENT BENEFICIATION PLANTS

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ABSTRACT. The majority of beneficiation plants face the need for revamp in the conditions of currently operating technology, equipment, and limited space of production units. Illustrating the example of two beneficiation plants processing apatite-nepheline ore (ANOF-2 and ANOF-3), we considered some aspects, steps and results of solving a number of tasks for revamp. In the course of the work, a comprehensive approach was applied, including: setting and clarifying the task, analysing the plant operation, identifying limiting factors, identifying possible ways to solve the problem followed by selection of the most appropriate way, determining the impact on the other process stages, implementing the planned activities, and assessing the efficiency of the work performed. We reviewed the elements of forecasting applied for beneficiation process indicators and modeling with some dependences considered. High efficiency of fine screening is proved, same as of column flotation and some other processes in the conditions of available spaces of the plants considered.

Keywords: beneficiation, apatite, nepheline, revamp, column flotation, beneficiation plants processing apatite-nepheline ore (ANOF-2 and ANOF-3)

НЯКОИ АСПЕКТИ ПРИ ПРЕУСТРОЙСТВОТО НА СЪЩЕСТВУВАЩИ ОБОГАТИТЕЛНИ ФАБРИКИ

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РЕЗЮМЕ. Болшинството от обогатителните фабрики са изправени пред необходимостта от преустройство в условията на непрекъснато действащи технология и оборудване и при ограничено пространство на производствените единици. Илюстрирайки с примери за две обогатителни фабрики за апатит-нефелинова руда (ANOF-2 и ANOF-3), разглеждаме някои аспекти, стъпки и резултати от решаването на редица задачи, свързани с преустройството. В хода на работата е приложен комплексен подход, включващ: поставяне и изясняване на задачата; анализ на работата на фабриката; идентифициране на възможните ограничаващи фактори; идентифициране на възможните начини за решаване на проблема, последвано от избор на най-подходящия начин; определяне на въздействието върху другите етапи на процеса; прилагане на планираните дейности; оценка на ефективността на извършената работа. Направен е преглед на приложените елементите на прогнозиране и моделиране на индикаторите в обогатителните процеси. Отчетени са и определени зависимости. Доказва се високата ефективност на финото пресяване, както и на флотационната колона и на някои други процеси в условията на наличните работни пространства на разглежданите фабрики.

Ключови думи: обогатяване, апатит, нефелин, преустройство, флотационна колона, обогатителни фабрики за апатит-нефелинова руда (ANOF-2 и ANOF-3)

Introduction

The implementation of a new production unit at a new location allows to apply the standard and already proven solutions, efficient (at the time of construction) technologies and equipment. However, in the process of operation, the production unit is supposed to be continuously improved. The following conditions may precede that: change in the properties of processed ores, the need to increase beneficiation and production indices, ageing of the existing equipment, and other factors. The revamp process consists of a number of stages. The goal of the initial stage is to determine the main criteria that need improvement or modification. In the course of work, these criteria can be specified, followed by data retrieval and identification of limiting factors of the existent production unit that prevent from achieving the assigned task. Then the possible ways to eliminate the revealed bottlenecks are identified. The general effect of the revamp on production is confirmed. Accordingly, the measures are developed and implemented to eliminate the bottlenecks, taking into consideration the integrated approach to solving the task. Thereupon, the efficiency of the completed works is assessed and synergy of operation of all process stages is specified. Based on this, a decision is taken on the need for additional work. At all stages, the decisions are evaluated and compared not only from the process point of view, but also from economic point of view.

In many ways, the revamp of the existent production unit is a more difficult task compared to the construction of a new one due to the necessity to consider the previously implemented solutions.

Some aspects of revamp of two beneficiation plants, ANOF-2 and ANOF-3, processing apatite-nepheline ore are considered below. These beneficiation plants are part of *Apatite JSC* ("PhosAgro" company, the Russian Federation).

The reasons for revamp and succession of tasks

At the time of commencement of the revamp (technical re-equipment) of the production unit, the considered plants had similar capacity for ore. ANOF-2 produced apatite concentrate (in the main production building) and nepheline concentrate (in a separate building) whereas ANOF-3 produced only apatite concentrate.

The reasons preceding the revamp of the production units were as follows:

- the necessity to shutdown the main production building of ANOF-2 due to its ageing (in operation since 1963) and high operating costs to maintain it;
- the need to increase the yield of apatite concentrate.

An important condition was to carry out works without reducing the yield of concentrates with maximum use of existent production areas and equipment.

The complicating factor was a continuous decrease in P_2O_5 content in the ore by an average of 0.07% per annum, currently it is about 12.5% (2018).

As a consequence, at ANOF-2, it was required to allocate a new space for the apatite concentrate production unit. The initial product supplied for the production of nepheline concentrate is apatite flotation tailings with a certain content of minerals. If the main amount of apatite concentrate is produced at ANOF-3 from ore rich in P_2O_5, the quantity and quality of the tailings may not be sufficient for the stable production of nepheline concentrate at ANOF-2. Reduction of content of the useful component in the ore requires a more complicated technological process. In case a non-flexible beneficiation process is applied, any fluctuations in composition inevitably lead to a decrease in process indices.

As a result of the analysis of the set tasks, the following sequence of solutions was proposed:

1. arranging of the nepheline concentrate production unit at ANOF-3, followed by its further shutdown at ANOF-2;
2. a step-by-step increase of capacity of the apatite concentrate production unit at ANOF-3;
3. the construction of a new process chain for the production of apatite concentrate at ANOF-2 within the nepheline production areas;
4. the shutdown of the main production building at ANOF-2;
5. further expansion of the new process chain at ANOF-2 in order to make possible the beneficiation of ores of different composition and further increase of the capacity of the apatite concentrate production unit at ANOF-3.

Such succession of tasks shall allow to use the existing areas and equipment as much as possible, as well as to carry out the revamp without reducing the yield of concentrates. Thus, as a result of transferring the nepheline concentrate production unit to ANOF-3, the issue regarding the compact placement of the apatite concentrate production unit at ANOF 2 is solved. Since poorer ore is processed at ANOF-2, as well as ore with a less stable composition, the production process shall stabilise at ANOF-3. The step-by-step transferring of the most functional flotation machines, with their preliminary renewal and re-equipment, from the main production building of ANOF-2 to the new flotation production areas will make it possible to reduce the amount of equipment to be purchased.

Arrangement of the nepheline concentrate production unit at ANOF-3

According to the project (as of 1979), it was planned to construct three identical production lines of apatite flotation in the main production building at ANOF-3. Additional space for the production of nepheline concentrate was not reserved.

By the time when the revamp began, two production lines of apatite flotation had been implemented. There were areas available for the construction of the third production line. To increase the yield of apatite concentrate, the third flotation line shall be ultimately required.

The tasks for the construction of the third line for apatite flotation and for the production of nepheline concentrate were considered together. This solution is reasonable because production units of both considered concentrates were planned to be placed within one production building of the beneficiation plant. Also, it should be taken into account that the production of nepheline concentrate is a sequential process following the production of apatite concentrate in terms of comprehensive processing of apatite-nepheline ores.

In this regard, it was decided to consider the possibility to implement a more compact version of the third line of apatite flotation (compared with the existent lines) within the available areas. And the production capacities of the lines should be similar.

As a result of the optimisation of technologies and the integrated approach regarding the layout solutions, the apatite flotation line and the nepheline concentrate production unit were placed within the areas reserved for one flotation line.

The flexible process chain of the nepheline concentrate production unit includes: segregation of the required volume of apatite flotation tailings, screening by their size, magnetic separation in a weak field, reverse nepheline flotation, and, if necessary, refinement of nepheline concentrate by magnetic separation in a strong field. It is possible to use the equipment at dehydration and drying stage both for nepheline and apatite concentrates. Filtration is performed via belt vacuum filters. Storing and load handling of the nepheline concentrate is arranged within the new areas.

Increase of the apatite concentrate yield at ANOF-3

The technology of the production of apatite concentrate at ANOF-3 included: three-stage crushing and one-stage grinding of ore with screening in hydrocyclones, the basic, control and three re-cleaning flotations, dewatering, drying, storing, and loading. Flotation is performed by pneumo-mechanical flotation machines OK-38.

Consideration of the process indices, test results, and further calculations proved that in a revamp process all major process stages are concerned, and it is reasonable to increase production capacity gradually by segregating the stages of work. This approach makes it possible to detail and correct the implemented solutions.

Analysis of the process schemes of new beneficiation plants (Baranov, 2004) shows that semi-autogenous ore grinding is the most common ore-preparation process. However, the introduction of this process at an existent plant shall require one-time drastic restructuring of the technological process with great financial investments.

This clearly does not fit into our general concept. For the revamp of ANOF-3, it was decided to gradually introduce modifications into the units which are limiting at this stage of general increase of production capacity of the plant. To identify the limiting factors, the following sequence of actions was performed: monitoring - measuring - calculating - analysing. Any of these actions may be skipped, and it is possible to come back to the previous action. This approach is used for all major process stages.

The performed calculations proved that the production capacity of the large crushing cycle would be sufficient.

At the stage of intermediate crushing, the screens GIST-72M were replaced with GTS 72MT (Korovnikov et al., 2013) and crushers KSD-3000T were replaced with GP7 (Metso Minerals). These measures, in addition to the increase of capacity, reduced the fraction size of fine crushing feed. The number of pieces of equipment did not change. It confirms the trend of the successful introduction of new crushers that operate as part of a standard ore preparation process which takes place mainly during the revamp of the operating beneficiation plants. At the same time, the obsolete equipment is replaced with new one.

Currently, the options for a revamp of the fine crushing unit are under consideration. The cone crusher MP-800 (Metso Minerals) was tested and commissioned.

It is important to arrange a rational load distribution between the stages of ore preparation, as well as between crushing and grinding. In our case, there is a task to increase the production capacity in conditions of limited spaces at grinding stage. In this regard, the issue of the increase of the efficiency factor of the crushing cycle, together with the reduction of a fraction size in the crushing-grinding cycle, has become very acute.

Taking this into account, one of the promising trends for a further revamp is the use of high-pressure grinding rolls (HPGR) at the final stage of crushing. The results of testing of ores processed at ANOF-2 and 3 by the use of HPGR confirm the possibility of efficient implementation of this technology within the existent production areas. In this regard, the development of a design for the installation of this equipment was started.

The sieving surface greatly influences the efficiency of screen operation. Currently, screening surfaces made of synthetic materials are widely used in the grinding cycle. The use of synthetic materials, in comparison with traditional metal surfaces, allows to increase their service life several times, to facilitate installation, and to reduce the extent of clogging. This leads to anincreased capacity due to the improving of the efficiency of screening and the equipment operating factor.

Increasing the capacity of the grinding process is possible by increasing the efficiency of screening. At the considered beneficiation plants, was applied a screening system several times by hydraulic size with the use of spiral classifiers (at ANOF-2) and hydrocyclones (at ANOF-2 and ANOF-3).

One of the trends in terms of increase of the capacity of the grinding cycle is the use of the fine screening process (Sukhoruchenkov et al., 2001; Baranov et al., 2005).

The results of the operation experience at the beneficiation plants (ANOF-2 and ANOF 3) showed that the curve of dependencies of apatite extraction on the grain size is typical with a reduced extraction of small (less than 20 μm) and large (more than 320 μm) grains of material into the apatite concentrate. The replacement in the grinding cycle of the screening process by hydraulic size for fine screening provides an increase in content of the most productive fractions in the flotation feed due to the reduction of the sludge content, the increase in the ore-grain release, and the reduction of the coarse fractions in the finished milled product. In the hydrocyclone, the separation of the material by its size is of a statistical nature, and in the hydrocyclone discharge, there are always particles of a much larger size that are considered to be the reference size for separation. Unlike the hydrocyclones, when screening into the sub-grid product, the material which is larger than the specified size does not pass through (in case of integrity of the screening surface). Also, the use of fine screening makes it possible to increase the capacity of a grinding cycle due to more efficient removal of the material of the required size from the circulating load of the mill. Compared to hydrocyclones, however, the screens have a number of drawbacks as well: lack of self-regulation of the process when the load changes, and there is often higher water content in the milled product.

Semi-industrial and further industrial tests of the fine-screening technology were conducted in 2006 (Brylyakov et al., 2006). Based on the test results, a step-by-step revamp of all existent mills at ANOF-3 was performed (Figure 1).

Fig. 1. The crushing unit at ANOF-3 after revamp

In addition, the total capacity of the grinding cycle was increased due to the installation of new mills that initially implied the use of screens. During the revamp of the mills, the circulating load decreased from ~ 400% to ~ 130% and the capacity increased by ~ 25-30% (Kalugin et al., 2014). An important point is that the revamp of the mills does not involve additional areas, and the content of solids in flotation feed varies insignificantly.

The earlier revamp of the mill automatic control system made it possible to achieve a capacity increase by 7-8% and increased the process stability.

The results of the analysis of process indices at ANOF-3 and further industrial tests proved the possibility of a step-by-step load increase at two existent apatite flotation lines. Their optimum capacities were determined that allowed to conduct the process without reducing the process indices. Currently, based on the performed calculations, the pumps that limited the production capacity of the lines are being replaced step-by-step.

The remaining excess load is routed (recycled) to further flotation lines.

While arranging for the third flotation line, the experience of ANOF-2 was taken into account. Thus, the results of semi-industrial tests at ANOF-2 in 2000 showed the potential applicability of column flotation machines for basic and control flotation. Compared to pneumo-mechanical flotation machines, column ones turned to be much more effective when used in the re-cleaning cycle. Thus, the use of this type of equipment made it possible to replace three re-cleaning units by one modification. This led to a reduction of the production area occupied by those re-cleaning units by about 2/3. In this regard, since 2006, after additional testing, flotation machines of this type are involved in the re-cleaning cycle of apatite flotation in the main production building of ANOF-2

The third line of flotation which was set in operation at ANOF-3 includes: basic and control flotation, as well as one re-cleaning which is performed by column flotation machines operating in parallel (Figure 2). The flotation machines of the ore and re-cleaning flotation cycles were step-by-step moved out from the main production building of ANOF-2. The diameter of the chambers of the column flotation machines is 4.6 meters; once they were set in operation, the height of the chambers was increased from 8 to 10 meters.

Fig. 2. Re-cleaning of the 3rd line at ANOF-3

The result of the already completed revamp work of theore preparation unit, flotation, the tailings facility, and other process stages has been an increase in capacity of the plant for ore by 2.3 times over the last 7 years. Besides, the nepheline concentrate production unit was established with use of approximately 1/3 of the total volume of apatite flotation tailings. A further increase in the yield of apatite concentrate is planned, and the possibilities for increasing the yield of nepheline concentrate are considered, as well as for expanding the range of concentrates produced.

Arrangement of a new process chain for apatite concentrate production at ANOF-2

The next, and in many respects more difficult, task is arranging the production of apatite concentrate at ANOF-2 in the production building of nepheline concentrate. The complicating issue here is the fact that, in future, the technology should allow processing not only of ordinary ore but also of poor and off-balance ores. After revamp, the existent crushing complex shall stay the same, the transportation of the crushed ore shall be performed by a conveyor of about 1000 meters long, and grinding shall be done in mills operating together with screens. The dewatering unit, previously used for the nepheline concentrate, has undergone drastic modifications. The thickeners were modified, a flocculant supply system was implemented, the vacuum filters were replaced, the automation system for all process stages was redesigned and expanded, and the flotation agent preparation section was reconstructed, as well as the tailings facility. Currently, the first production line was started-up using the slurry supplied from the main production building. Flotation includes: basic, control, and one re-cleaning operation. The OK-38 flotation machines, previously used in the production of nepheline and apatite concentrates at ANOF-2, are used for the main and control flotation. Six column flotation machines with chambers of 4.6 meters in diameter and 8 meters in height are used in the re-cleaning flotation. Four column flotation machines are being transferred from the main production building, two are under purchasing. At the time of writing of this article, two transferred column flotation machines are operated (Figure 3).

Fig. 3. Re-cleaning of apatite concentrate in the former nepheline concentrate production building at ANOF-2

When developing and analysing the beneficiation options, the modelling of the process was done involving a number of dependencies.

The analysis of processes indices and lab tests for different ores and beneficiation processes has revealed a clear linear relationship between the amount of the target component passing to the concentrate (γ*β) and the content of this component in the ore (Klemyatov et al., 2011). Thus, having a data array for the operation or for the entire technological process, we can consider the following dependence:

$$\gamma \cdot \beta = a \cdot \beta_{feed} + b \quad (1)$$

where:
γ is the concentrate yield (in %);
β is the component content in the concentrate;
β_{feed} is the component content in operation feed (in %);
a and b are equation coefficients.

At the same time, there is a close to linear dependence of the concentrate yield on the content of the target component in the ore.

In this regard, for each operation of beneficiation flotation cycle, there were found the coefficients of the regression equations linking the main beneficiation indices. The coefficients of the equations were calculated based on the array of the flotation process tests performed during the beneficiation of ores with different P_2O_5 contents. For the re-cleaning flotation, another regression equation term was added which is responsible for the effect of the apatite concentrate quantity (produced by one column of the flotation machine) on the beneficiation indices.

Then, by iterative calculations, the expected values for the intermediate beneficiation products were determined. The process configuration was designed taking into consideration the real possible layouts of the equipment, due to strict limitations in terms of spaces and elevations, and the need for self-transportation of products by gravity.

The approach using this or similar equations is quite universal. Here, it was used for forecasting of the final beneficiation indices, for estimating the effect of line ore load on the beneficiation indices, for identifying process failures, and in a number of other cases.

For example, when evaluating the effect of ore quantity (supplied into the processing from different mines) on the beneficiation indices and forecasting the beneficiation indices of this ore, the following option of the considered dependence can be applied (the simplest option is provided):

$$\varepsilon = \frac{\beta_{ore\Sigma} \cdot \sum (\gamma_{ore(n)} \cdot a_{\varepsilon(n)}) + b_{\varepsilon}}{\beta_{ore\Sigma}} \quad (2),$$

$$\gamma = \beta_{ore\Sigma} \cdot \sum (\gamma_{ore(n)} \cdot a_{\gamma(n)}) + b_{\gamma} \quad (3)$$

where:
ε is the extraction of the considered component into the concentrate (%);
γ is the concentrate yield (%);
n is the trend of ore supply;
$\beta_{ore\Sigma}$ is the contents of the considered component in the ore supplied to the plant (in %);
$\gamma_{ore(n)}$ is ore fraction in the trend of the total ore supply to the plant (in %);
$a_{\gamma(n)}$, $a_{\varepsilon(n)}$, b_{ε}, b_{γ} are equation coefficients.

Currently, an option is being elaborated for the second re-cleaning flotation for the implemented process. Considering the area limits for this operation, the possibility of using pneumatic flotation machines is considered: Pneuflot, Jameson Cell, or similar ones.

Conclusion

The example of the two beneficiation plants has shown that the process of revamp of existent production units requires a systematic approach. According to the authors, the process of revamp of the plant should proceed almost continuously from its start-up to its shutdown due to a constant change of ore composition, optimisation of operation parameters and new processes emerging, the existent equipment getting obsolete, and new equipment developed. An important factor is achieving maximum profit with minimum operating costs.

When choosing the options for revamp, we considered not only the process indices, but also compared the expected economic effects. A positive economic effect has been achieved for already completed upgrades. Calculations show that a positive economic effect is also expected from all works currently performed.

The methods for solving each task can vary and there are no unambiguous templates to follow. The main thing is always to keep to a systematic approach and consider more than just a local issue.

As a result of the already completed activities for the revamp of ANOF-2 and ANOF-3, the total yield of apatite concentrate at the two beneficiation plants has increased by 1.2-1.3 times over the past seven years and a further capacity increase is planned.

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