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Research paper

Heap leaching. Computer simulation as an alternative technology

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Abstract

The article discusses the possibility of reducing environmental risks and resources by finding ways to optimize technology solutions with a computer program that simulates the heap leaching process. It is shown that the main role in the design and operational control plays simulation and an understanding of the structure and movement of the concentration fronts of substances – leaching participants within the heap. The examples of process control by conventional technological parameters – density of irrigation, fineness crushing or agglomeration bulk and height of the heap – show the attainability a significant reduction in of leaching time and as a result, reducing consumption of energy, water and sodium cyanide. The latter is a major threat to the environment.

Keywords: Heap leaching; Computer simulation; Alternative technology

1. Introduction. Statement of the problem

Heap leaching of precious metals from low-grade ores is highly resource- and energy-intensive process. Lots of heap leaching occupies dozens and sometimes hundreds of hectares of land. In the reverse process at the same time there are hundreds of thousands of cubic meters of toxic sodium cyanide solution. This circumstance represents a significant threat to the environment. Engineering measures taken to protect and prevent possible risks do not eliminate completely the cases of defeat on the surrounding countryside and surface and ground water [1,2].

Reducing the potential risks is achievable with decreasing volumes in circulation solutions that must lead to significant energy savings and reduced consumption of sodium cyanide per unit of output. Searching for opportunities to optimize the heap leaching process by conscious choice of control models can play a significant role in solving the problem of reducing environmental risks and resource.

Heap management is performed in two stages. In the first stage of design as a result of preliminary laboratory and sometimes semiindustrial study of the properties of ore and on the basis of gained experience designers the requirements for the ore fractional composition and the heap geometric parameters are formed. We do not consider here the economic component of the design process, although it also plays a very important role in the choice of a particular technological solution.

After the formation the heap enters a stage of irrigation and metal recovery. The current process control practice of the heap leaching of gold is to regulate the flow of the working solution at the pH and concentration of sodium cyanide and density irrigation. The result is a change of gold concentration in the pregnant solutions arising from the heap. The experience gained by the technologist allows partially to optimize the process for product cost and other economic and technological indicators.

The search for formal criteria to achieve the optimal parameters is an important task of the entire heap leaching technology [3,4].

An optimization problem may be well solved in the presence of a formalized numerical model of the process. Currently, there are different approaches to the creation of numerical models [5–8]. However, the achieved level of formalization of the problem does not allow technologists to obtain fairly complete and comprehensible description of percolation and chemical processes within the heap using existing approaches and software.

The principal drawback of the existing models is a complete lack of information on the state of the heap and current distribution of substances – participants' cyanidation in the inner

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layers of the heap. Experiments on the columns 10–12 m height allow us to obtain the uninformative distribution of substances in the end of the leaching cycle, but do not allow to monitor the situation in real time. For this reason, the information received in such a way has very limited application and may not be practically used for designing or controlling the actual heap. Consequently, in the current literature the question of the internal state and the distribution of chemicals within the heap is not considered due to the lack of approaches to solve the problem. But this very information is necessary for cost-effective and resource-saving solutions search.

The software simulating the heap leaching process considered in this paper may help to overcome such difficulties. This process is similar in the form to the movement of the trailing edge in the frontal chromatography by washing the chromatographic column from the sorbed substance. Such a view makes it possible to understand essentially the process of leaching, although the precise description of the expenditure of sodium cyanide within the heap has some specific features that do not adequately develop this analogy further.

2. Results

2.1. Description of mathematical models and software

Heap is considered as granular medium with a flow passage between the pieces of ore and non-flowing channels inside pieces of rock or agglomerates. Block of hydrodynamic equations is based on the well-known and fairly comprehensive van Genuhten [9] model, which allows to simulate flows in granular media in both saturated and unsaturated mode. This model is supplemented by equations describing the kinetics of the interaction of cyanide solutions with gold and impurity metals absorbing sodium cyanide as it flows through the ore layers and the equations of exchange solutes between flowing and nonflowing channels, carried out mainly by diffusion. Thus, the programme skeleton has more than a dozen of partial differential equations and equations of exchange. With the increasing complexity of the fractional composition of the ore or the number of irrigated tiers or heaps at the same time the number of solved equations has grown significantly, but, nevertheless, it has a little effect on the duration of the simulation. The simplest model of the heap having single fraction in one layer is calculated on a standard PC within minutes. Calculation of more complex multi-tiered and multifractional model may take hours.

The programme menu is made in Russian.

The model of single heap or complex flowsheet is created from separate blocks, allowing designer to collect sophisticated variants site heap leaching like in tinker toys. Each heap may consist of a set of fractions that differ in their kinetic and hydrodynamic parameters, gold content and exchange constant between the flowing and unflowing areas. Heaps can be irrigated in parallel or in series, which allow to carry out simulation of recirculating irrigation regime or multi-tiered pile with consistent showering on the upper tiers as mining lower.

Here the monitor displayes in the real-time distribution curves within the heap of sodium cyanide and leachable gold inside of agglomerates in the solid phase and passed into the solution, and solutions for flow and stagnant zones separately.

There is a continuous calculation of solutions casted on a bunch in terms of volume and sodium cyanide weight and cyanide solution in heap and their output from the heap. Also the balance of gold is estimated and this information is also available in real time.

This information allows to search for a targeted technological solution that reduce the consumption of water, electricity, sodium cyanide and critically reduces the cyanidation time and related environmental risks.

2.2. Physics of the leaching. Movement of concentration fronts

For further analysis, we have modeled the classical dependence of the concentration of gold in the product solution on time – the kinetic curve – with very plausible parameters for clay or silty ores (Fig. 1).

These hereinafter illustrations are arranged from the actual windows as they appear on the screen at a time stop counting.

As an example we take into consideration the element of heap of 1 m area and 6 m high, of single fraction, while the time of diffusion exchange $\mathbf{T_{diff}} = 100$ hours, the concentration of [NaCN] = 0.2 g/l, density irrigation $\mathbf{j} = 5$ l/m^2 * h.

Here and below, for ease of comparison of the curves, we shall provide the data for the end of the process when it reaches 95% of the production of leachable gold. The obtained results on the consumption of sodium cyanide, solutions (and electricity) can be easily converted to a bunch of any size. In practice, there are heaps, markedly different from the one proposed, but we have chosen this because of its high ductility, i.e. clear and pronounced response in the behavior of the heap to changes parameters characterizing both ore and leaching process.

On the curve there are two expressions area: peak and shoulder. It is natural to expect that the physics of the leaching process is also different for the two parts of the curve.

As stated above, the computer simulation of the leaching process allows us to see what happens with the substances – participants in the thickness of the heap. The Fig. 2 shows the

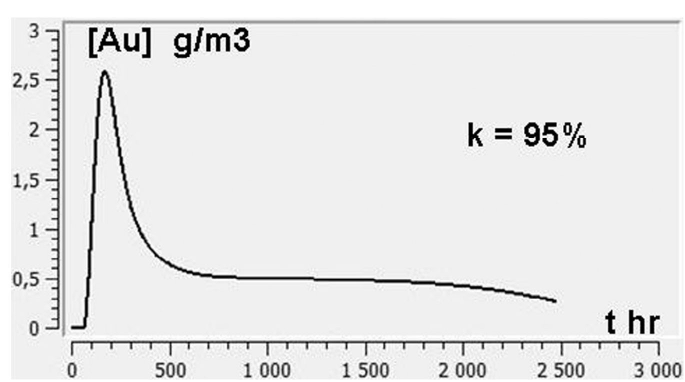

Fig. 1. The kinetic curve of the initial model experiment. The main important parameters: heap height is 6 m, recovered gold coefficient is 0.95, the concentration of gold extracted is 1 g/t, the concentration of [NaCN] is 0.2 g/l, the density of irrigation $\mathbf{j}$ is 5 l/m^2 * hour, time diffusion transfer $\mathbf{T_{diff}}$ is 100 hours.

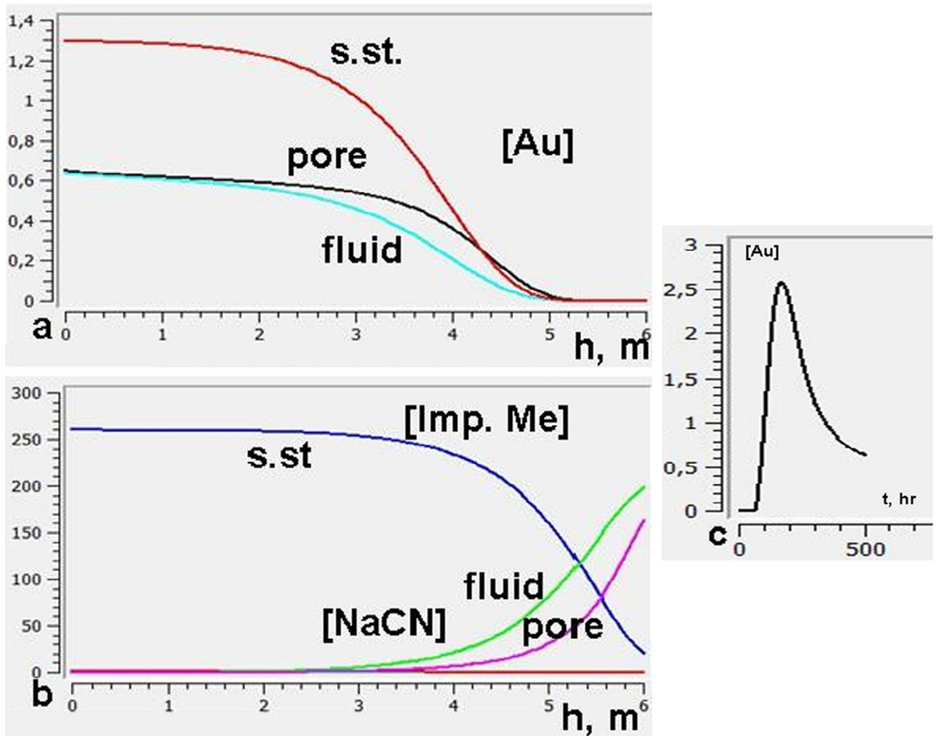

Fig. 2. Formation of the concentration fronts of cyanidation participants within the heap. Legend**: h, m** – vertical coordinate within the pile measured from the lowest point; **[Au], [Imp. Me], [NaCN]** – concentration respectively of gold, the impurity metals and sodium cyanide in g/t of ore or solution; **s.st –** concentration curve for the solid phase; **pore –** concentration curve for the solution in the pores inside the granules; **fluid –** concentration curve for the solution flowing between the granules.

fixed moment of time equal to 500 hours from the beginning of the heap irrigation, as seen in the kinetic curve (2c).

By the nature of the curves (2a and 2b) we see that by 500 hours the formation of concentration fronts on all major components is completed. The front is a transition region between the concentrations of the component, set in the upper and lower points of the heap. This transition region is theoretically always formed and may be more or less pronounced in high enough (unlimited height) heap. In a real situation, it is obvious that the width of the front can be either greater or less than the height of the heap. In the current case, the front width is approximately 2 m.

It should be noted that the formation of the concentration front is not only measured by spatial extension, but also by the time required for its formation. It means that the ratio control front width and height of the pile can be carried out both the change of spatial or temporal parameters and their simple or functional combination.

Fig. 3 shows the distribution curves of gold-components for 500 and 2000 hours of leaching. As can be seen, the concentration fronts move to the bottom of the heap in the quasi-stationary regime, almost without changing their positions relative to each other. Figure allows us to calculate the velocity of the front, which is 1 m high for about 500 hours. It allows us to determine the time for fronts on the lower edge of the pile – 2500 hours – and thus to predict the end time of the leaching process.

Fig. 4 shows the dependence Au extraction of sodium cyanide consumption. As the feed mode cyanide is 1 g/h, the time scale of hours may be adopted for the scale cyanide consumption in grams. As can be seen, there are two characteristic regions. The plot is becoming fronts (transient) corresponding to the peak on the kinetic curve, and the fronts movement phase (quasi-stationary) corresponding to the shoulder, with very different specific consumption of cyanide. Lower cyanide consumption in the initial section is consistent with the high content of gold in pregnant solutions at the beginning of the kinetic curve. The logical question has come up whether it is possible to extend the length of the non-stationary region, achieving thereby increase of gold concentration in the pregnant solution and, as a consequence, reduction of the leaching time and more economical use of cyanide. On the present curve two values are principal for further discussion – the total time of leaching equel to 2480 hours and cyanide consumption equel to 2360 g to extract 95% of the gold.

Let’s try to increase the density of irrigation tripled to 15 l/m^2 * hour in the hope that by the increased speed of the solution the front will be degraded and will become much wider.

Fig. 5 shows the distribution curves and kinetic curve at the end of the leaching process. As can be seen, the fronts have really stretched almost for the entire pile. With the increasing density of irrigation flow rate of cyanide has also tripled, but at the same time cyanidation period has decreased by more than four times from 2480 to 580 hours. The consumption of cyanide is reduced from 2360 g to 1560. Thus, only increasing the supply of cyanide by increasing the density of irrigation it is

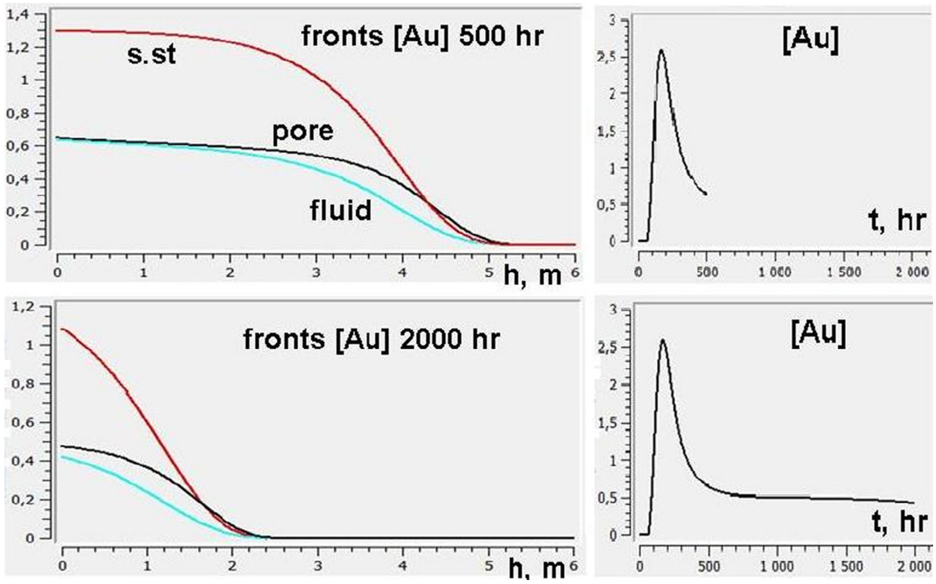

Fig. 3. Comparative location of concentration fronts for gold-components for time cyanidation 500 and 2000 hours. The notation is the same as in Fig. 2.

impossible to explain the observed values in full. A significant role is played by the stretching of the concentration fronts.

Note that the absence of a shoulder on the kinetic curve determines that no characteristic of the quasi-stationary process is observed on the curve of consumption of sodium cyanide.

The simple increase of the concentration of sodium cyanide in threefold to 0.6 g/l while maintaining a low water concentration is 5 l/m2 * hour also reduces the cyanidation time, but not 4 or even 3, and only 2.5 times up to 910 hours, and cyanide consumption even increases in comparison with the original one. At the same time the specific shoulder of quasi-stationary process is preserved on the kinetic curve.

It is possible to achieve concentration fronts stretching within the heap by slowing a process of diffusion exchange of cyanidation products between the lumps or pellets of ore and flowing solution, ie, by increasing the time of exchange.

Fig. 6 provides information about the experiment with the same parameters, but within the time of the diffusion exchange is equel not to 100, but 500 hours. It can be achieved by formation of larger granules or larger crushing ore.

We observe that even in this case, at a low water irrigation 5 l/m^2 * hr concentration fronts stretching occurs over practically the whole pile. Compared with the initial experience, this leads to a reduction in cyanidation time to 1670 hours and reduction of the amount of spent cyanide to 1460 g. Thus, we spent less than a third time and water and use up to 40% less of sodium cyanide. Note that the result does not correspond to

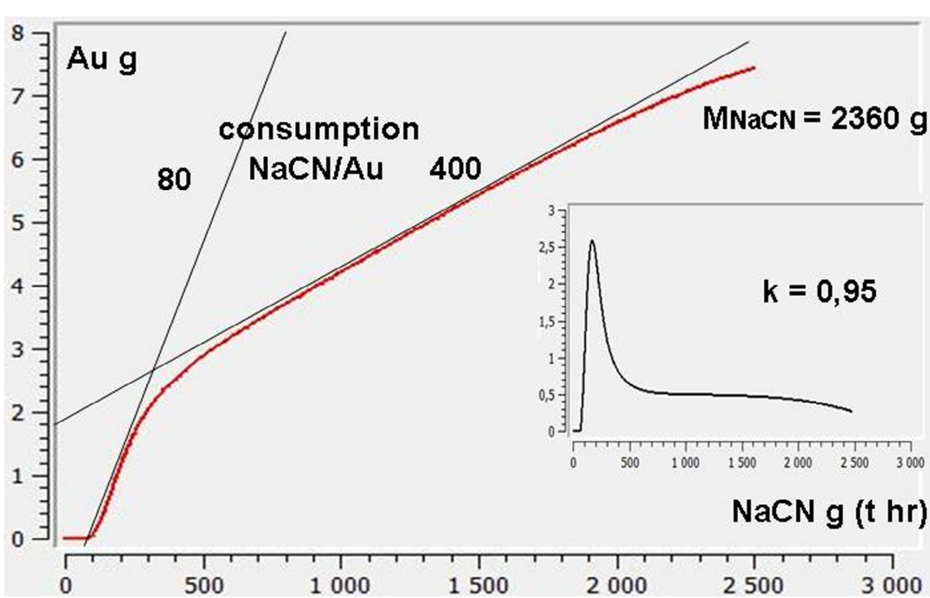

Fig. 4. Dependence of the yield of gold from cyanide spent.

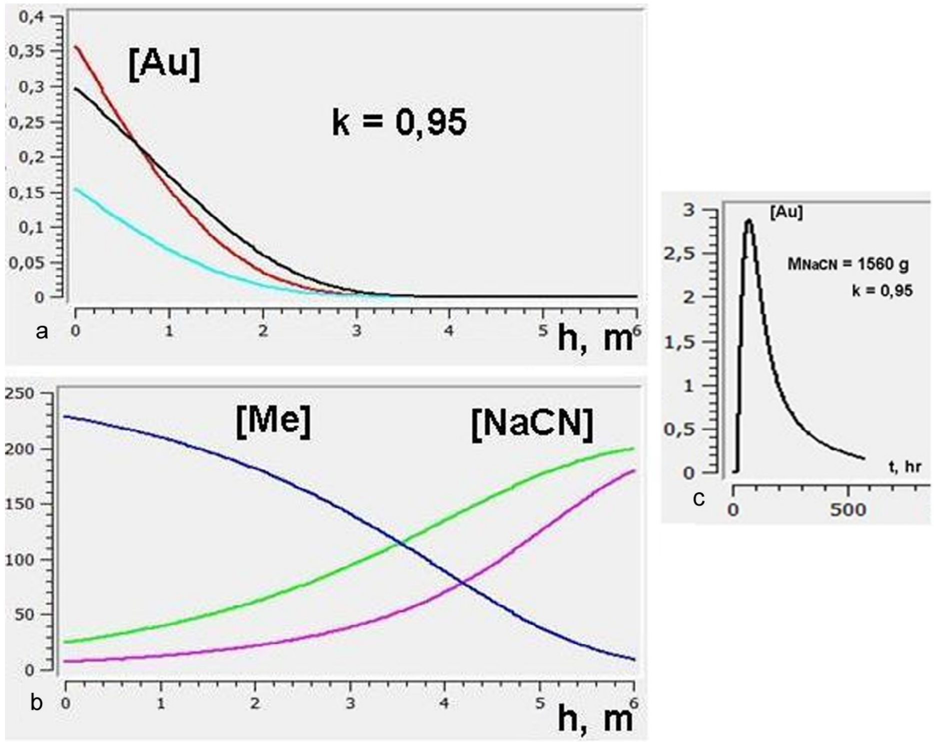

Fig. 5. Distribution curves (a and b) and the kinetic curve (c) for the initial heap (Fig. 1) with increased water concentration to **j** = 15 l/m^2* h. The notation is the same as in Fig. 2.

popular belief that the larger the crushed ore is, the longer and more difficult the leaching process is.

Fig. 7 shows what we can expect from the heap, if it is possible to increase the values of two parameters – the density of irrigation, and the time of diffusion exchange. As can be seen, at such parameters of ore in a heap of 6 m high concentration fronts do not have time and length to form. In this case, the pile of 10 m high or more would be acceptable. Leaching time reduced to 630 hours, and cyanide consumption was the least or record low in this series of experiments – 980 g. This

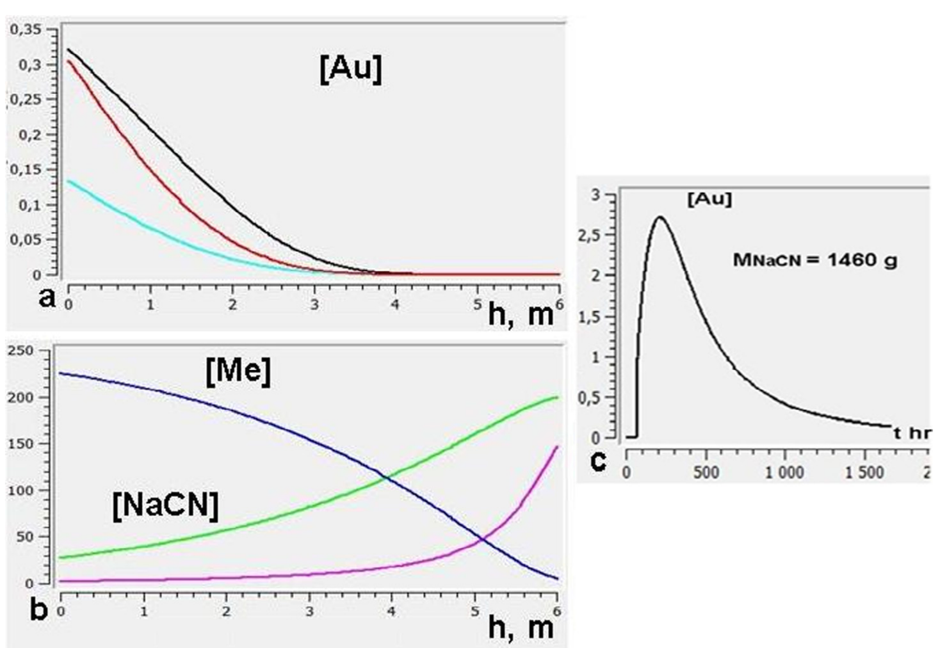

Fig. 6. Distribution curves (a, b) and the kinetic curve (c) for the initial heap (Fig. 1) with extended time of diffusion transfer $\mathbf{T}_{\mathbf{diff}}$ = 500 hours. The notation is the same as in Fig. 2.

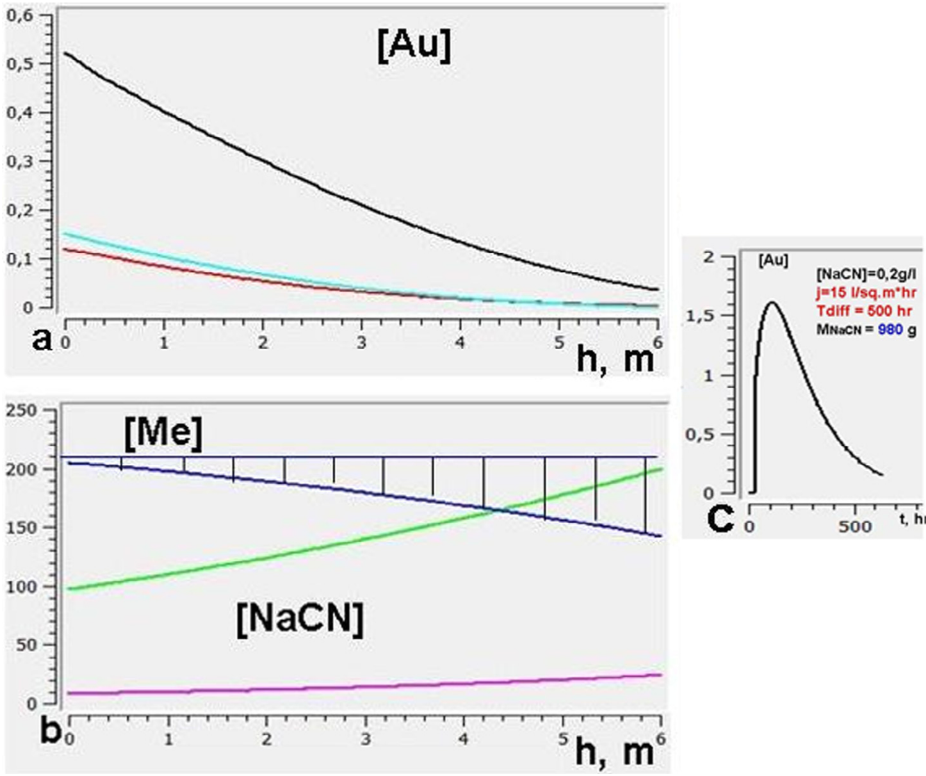

Fig. 7. Distribution curves (a, b) and the kinetic curve (c) for the initial heap (Fig. 1) by increasing the density of irrigation **j** = 15 l/m^2 * hour and diffusion transfer time $\mathbf{T_{diff}}$ = 500 hours. The notation is the same as in Fig. 2.

fact can be understood by type of the front of impurity metals concentration by the end of the leaching process. Horizontal line marks the initial concentration of impurities, the line under it – the ultimate. The hatched area between these lines corresponds to the amount of dissolved impurities and determines cyanide consumption spent on them. As can be seen in comparison with previously presented data, in this case the hatched area is minimal, and that defines the minimum expense of cyanide. In all the examples cyanide consumption of about 5 g on the dissolution of gold itself is neglected due to its insignificance compared to the total consumption.

2.3. Process control

In a situation where neither the density of irrigation or exchange diffusion time can be changed for the better can somehow affect the cyanide process? If we follow the original experience, the concentration front width is about 2 meters. Taking into account our desire to work in a transient mode, the height of leached layer should be no more than 2 m. Thus, we can work out the same amount of ore as in a pile of 6 m high, but by dumping gradually three tiers of 2 m high one to another without intermediate waterproofing. At the beginning the first tier is leached for 600 hours, then the second tier is leached for 600 hours. Also, after the second tier the third tier is leached. At each stage each layer is leached until 95% of gold extract, or slightly more, so that taking into account the residual gold the ratio of the total extract is not less than 95%. Irrigation regime and the properties of the ore remain unchanged.

Fig. 8 shows the kinetic curves of two experiments: the usual six-meter pile and subsequently backfilled 2 m high three-tiered piles of the same volume. As seen, the increase in the average concentration of gold in pregnant solutions in the latter case results in reduction of time of leaching to 680 hours (28 days). The sodium cyanide consumption has reduced significantly from 2360 g to 1745 g. It should be noted that reduction in the time of cyanidation is extremely important when working in harsh environments, where production is limited to the warm season and we have to get the maximum extraction in a limited time until the first frosts.

Results of described model experiments are summarized in Table 1.

We provide an opportunity for the reader to perform analysis of the values listed in the table of process parameters and draw the appropriate conclusions according to their preferences.

3. Conclusion

The above examples clearly show that in heap leaching, as in many areas of engineering and technology, where the real experiment with the object is too expensive and often not repeatable, computer simulation is an indispensable tool of search for optimal solutions. In the heap leaching energy and resource efficiency are key indicators of economic efficiency. Reducing the volume of consumable fluids and acute toxic chemical agents, as well as time cyanidation we significantly reduce the harmful impact on the environment and the level of accident risk.

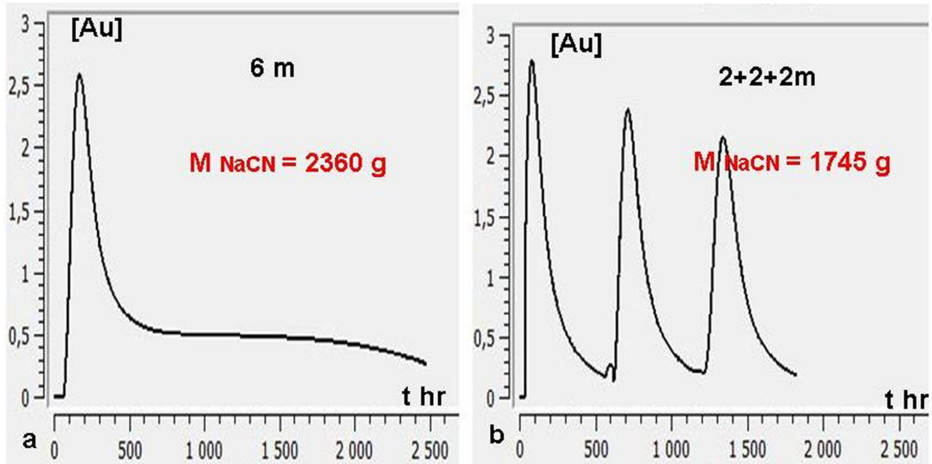

Fig. 8. Kinetic curves of the original heap height of 6 m (a) and a three-tiered heap of the same volume. All parameters are identical Fig. 1.

The above proposed approach to the description of processes in heap leaching through the dynamics of the formation and motion of the concentration fronts in the heap is completely new and has only been possible thanks to the creation of software used. The issue of improving the software in terms of the inclusion of new control parameters for the purpose of successive approximation to the description of the actual piles is a matter of accumulation of experience of its application and development of experimental techniques required for the expansion of parametric base.

Table 1
Test conditions and results of model experiments. Experience 5 differs from the experience 1 by way of lying of ore in a heap.

	j l/m^2*h	T_{diff} h	T_{extr} h	M_{NaCN} g	L : S m^3/t	NaCN/Au
1	5	100	2480	2360	1.59	320
2	15	100	581	1560	1.12	210
3	5	500	1670	1460	1.07	197
4	15	500	630	980	1.21	126
5	5	100	1800	1745	1.15	234

Designations: **j –** flux density of irrigation in l/m^2 * h; $\mathbf{T_{diff}}$ – time diffusion exchange in hours; $\mathbf{T_{extr}}$ – leaching time in hours; $\mathbf{M_{NaCN}}$ – mass cyanide consumed in grams; **L: S** – m^3 amount of solutions used for 1 ton of ore; **NaCN/Au** – NaCN consumption in grams per 1 g Au.

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