Environmental impact assessment of gold underground leaching technology

A N Kutliahmetov1, A A Kulagin1, F F Iskhakov1, I R Rakhmatullina1, N R Nizamutdinova2, G F Shaidullina2 and V I Safarova2

1 Akmulla Bashkir state pedagogical university, Ufa, Russia
2 GBU RB “UGAK”, Ufa, Russia

E-mail: ecobspu@mail.ru, ugak@ufanet.ru

Abstract. The research assessed an impact of the underground gold mining (GM) on snow cover, surface and ground water of the industrial site and the adjacent area. It has been established that the water of observation wells located downstream the terrain contains specific pollutants typical for the GM technology. The snow cover contains dust, heavy metals, arsenic and some light organochlorine compounds, which are components of GM solutions. The article also gives recommendations on monitoring and assessment of the environmental impact of the PoE technology.

1. Introduction
The gold mining industry in the territory of the Republic of Bashkortostan (RB) has almost a 200-year history. During this time various technologies were used for processing of gold placers and gold-bearing ores [1, 2]. According to many professionals, the modern base of traditional technologies has reached its limits [3, 4], so the use of new geotechnological methods is timely and relevant. In particular, underground gold mining (GM) is one of the most economical innovative technologies in the gold mining industry [5–8].

At present, there are about a dozen industrial facilities at GM in the Middle Urals, which are at different stages of development. The first enterprise in Russia to apply the underground leaching method for gold mining in 1994 was ZAO Gagarka-Ai-PV [5, 19, 20].

Taking into account the economic attractiveness of the GM method, which makes it possible to conduct a complex geo-technological process at minimum cost, it is possible to assume its wide introduction into the practice of gold mining. In this regard, an objective assessment of the environmental safety of GM production is extremely important.

2. Problem Statement
The GM principle in its classical variant at favorable combination of natural factors (seismic, geotechnological, lithologic-geochemical, hydrogeochemical) is simple. Several dozens of wells are drilled in the ore body. Some (injection) wells are supplied with leaching solution, while others (pumping) are used to extract productive gold-containing solution for further processing. The GM method creates an opportunity for cost-effective mining of deposits or their individual areas, which differ from the complex mining and geological conditions of occurrence, low-power deposits, deposits with low gold content in the ore [9–12].
An important advantage of the GM technology in comparison with traditional methods of polymetallic deposits development is insignificant negative impact on the environment, as the landscape is practically not disturbed and the fact that the formation of solid waste of ore processing is prevented. It also eliminates the most expensive operations, such as ore extraction, transportation, and mechanical processing of ore prior to dressing.

Calcium or sodium hypochlorite produced by electrolysis or gaseous chlorine is used as a reagent for gold extraction [13, 14]. Due to the initial toxicity and aggressiveness of leaching reagents, special attention is paid to ensuring industrial safety, reducing the corrosion hazard for process equipment, as well as environmental protection [7, 8].

Pollution of natural environments at PoE is usually reduced to the impact on the aquifer compounds used in the technology and formed in the process of gold extraction (chlorine, active chlorine, chlorine ion, heavy metals) [8, 12, 15]. In works [5, 12, 16–18] it is noticed that pollution has local character, but represents potential danger, as in the course of underground leaching, hammocks and after hundred end at recultivation of underground aquifers.

The SP technology is characterized by a number of features: there is a large inertia of the process due to the fact that leaching takes place in the bowels; the main object of impact is the aquifer, which is difficult to manage [19]; the existing system of environmental monitoring in the zone of influence of SP technology requires improvement.

3. Research Questions
On the basis of experimental data on the condition of air, water and snow samples taken in the zone of influence of gold mining companies that use the technology of underground leaching, to assess the environmental safety of the technology.

4. Purpose of the Study
The objective of the work is to assess the negative impact of the gold leaching technology on the snow cover, surface and ground waters of the industrial site and the adjacent area.

5. Research Methods
Samples of natural and ground waters were taken in accordance with GOST R51592-2000, GOST 17.1.5.05-85, samples of atmospheric air and snow were taken and studied in accordance with recommendations of RD 52.04.186-89. Selection points were located at a distance of 20 m from the site boundary and at the boundary of the sanitary protection zone (300 m from the site of the underground leaching unit of BPV No. 5) along the main channels and in the direction of the prevailing wind.

Chemical-analytical studies of air, water and snow cover samples were performed in the accredited laboratory of SBURBUGAK (No. RU.0001,510312) with the use of certified methods based on classical and modern methods of analysis – titrimetry, photometry, atomic absorption spectrometry, chromatography and chromatography of mass spectrometry.

6. Findings
The impact of WP on natural waters is in the change of hydrodynamic regime, inflow to the aquifers of leaching solution containing a highly effective oxidizer – hypochlorite ion (active chlorine). As a result of chemical processes occurring during the interaction of the leaching solution with ore minerals, gold turns into a solution in the form of soluble salt [1]. Together with gold, heavy metals present in the ore are transformed into a soluble migration-active form: copper, zinc, cadmium, lead, mercury, etc. Besides, high oxidative capacity of active chlorine causes chlorination of natural organic compounds present in underground waters. These are water humus, lignin-like substances, cellulose and other natural and organic substances, with the interaction of active chlorine with which highly toxic organochlorine compounds are formed.

The technological process of obtaining gold by PV method includes the following stages: preparation of leaching solution (chlorine solution in water); injection of leaching solution into ore-
bearing zone; control of solution movement in the bowels; lifting of productive solution to the surface by ellipsis; capture of residual chlorine of ellipsoidal air; clarification of the productive solution from mechanical impurities; extraction of gold, silver, other useful components, as well as contaminants from the productive solutions; capture of mechanical losses of sorption containing gold [3, 8, 9, 14, 19].

The scheme of the in-situ leaching technological process is shown in Figure 1.

![Diagram of the in-situ leaching process](image)

**Figure 1.** Scheme of the underground leaching process

*Results of the survey of process and natural waters.*

The results of the analysis of water samples taken in the operational area of the BPV5 (Figure 1) and in the area of its influence are shown in Table 1.

The technological productive solution of the SP enterprise is characterized by low pH (3.2), high biobromate oxidation (COD 111 mg O2/l) and mineralization (7840 mg/l), high concentrations of hypochlorite ion (118 mg/l), chlorides (4110 mg/l), macro components (calcium, magnesium, sodium, potassium, aluminum), as well as heavy metals, including highly toxic elements (mercury, cadmium, lead, etc.).

The presence in technological solutions of a large number of volatile and low-volatile chlorinated hydrocarbons [21] creates a potential risk of their spread in the underground aquifer, outside the technological area of the SP in the event of cessation of pumping solutions.

Results of the snow cover survey. Snow cover accumulates atmospheric deposition of pollutants during the snowstorm period (about 6 months), which makes it possible to use snow as an indicator of airborne environmental pollution.
Sources of atmospheric air pollution in the area of PoE plant location are industrial emissions formed at the stage of leaching solution chlorination [21].

Investigation of snow cover samples included determination of the main indicators of water quality (pH, suspended solids and dry residue content), inorganic anions (chlorides, sulphates, hypochlorites) in melt water filtrates. The content of heavy metals and arsenic was determined separately in filtered melt water and solid snowfall. Organic compounds were determined from unfiltered snow samples.

### Table 1. Content of substances in the underground waters of the industrial site of the PoE enterprise and the adjacent territory, mg/dm$^3$

| Definable indicator | Productive mortar | Technological well | Observed wells | Water well |
|---------------------|-------------------|--------------------|----------------|------------|
|                     | Higher ground     | Lower ground       | well 1         | well 2     | well 4 | well 5 | well 6 | well 7 | well 8 |
| pH                  | 3.2               | 3.2                | 3.7            | 7.8        | 8.9    | 8.0    | 8.1    | 7.8    | 7.9    | 8.2    |
| x n k               | 111.0             | 35.0               | 27.0           | 12.5       | 51.0   | 21.5   | 6.0    | 6.0    | 12.0   | 6.0    |
| Dry residue         | 7840              | 8410               | 5800           | 545        | 267    | 388    | 530    | 408    | 308    | 475    |
| Hypochlorithione     | 118.0             | 208                | 132            | <0.05      | <0.05  | <0.05  | <0.05  | <0.05  | <0.05  | <0.05  |
| Chloride ion         | 4110              | 4060               | 3515           | 90.4       | 81.2   | 46.0   | 37.0   | 53.0   | 7.4    | 8.9    |
| Sulfate ion          | 86.0              | 38.0               | 55.0           | 73.0       | 33.0   | 87.0   | 104    | 63     | 33     | 50     |
| Fe                  | 1.03              | 0.38               | 0.21           | 0.49       | 0.16   | 0.15   | 0.59   | 0.21   | 2.79   | 0.06   |
| Mn                  | 0.13              | 0.02               | 0.03           | 0.77       | 0.15   | 0.05   | 0.03   | 0.04   | 0.85   | 0.01   |
| Cu                  | 65.7              | 54.2               | 31.8           | 0.025      | 0.06   | 0.01   | 0.014  | 0.007  | 0.023  | 0.005  |
| Zn                  | 90.5              | 72.1               | 44.9           | 0.15       | 0.03   | 0.05   | 0.03   | 0.03   | 0.14   | 0.03   |
| Hg                  | 0.03530           | 0.0536             | 0.0967         | 0.00009    | <0.0001 | 0.00077 | 0.0004 | 0.00001 | 0.0001 | <0.0001 |
| Cd                  | 1.416             | 1.053              | 0.612          | 0.0004     | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |
| Pb                  | 0.395             | 0.223              | 0.135          | <0.0006    | <0.0006 | <0.0006 | <0.0006 | <0.0006 | <0.0006 | <0.0006 |
| Summ of i           | 18.8539           | 17.1607            | 13.6547        | 0.0261     | 0.0322  | 0.019  | 0.0039 | 0.0016 | 0.00046 | <0.0004 |

The results of the analysis of snow cover samples are presented in Tables 2 and 3.

### Table 2. Content of inorganic pollutants (IP) in snow samples taken at the IP plant site and in the area of its influence, mg/dm$^3$

| Definable ingredients | Industrial platform | west | north | east | south-east | The outskirts of the Semenovskoye village | MPC fish farm. |
|-----------------------|---------------------|------|-------|------|------------|-----------------------------------------|----------------|
| pH                    | 4.2                 | 5.0  | 5.0   | 5.2  | 5.6        | 4.5                                    | 4.2            | 5.5 | 5.5 | 6.8 | - |
| Weighted substances   | 84                  | 52   | 52    | 34   | 39         | 27                                      | 27             | 52  | 28  | 67  | - |
| Hypochlorithione      | <0.05               | <0.05| <0.05 | <0.05| <0.05      | <0.05                                   | <0.05          | <0.05| <0.05| <0.05| <0.05|
| Chloride ion          | 215                 | 3.1  | 3.1   | 2.5  | 2.8        | 17.0                                    | 3.8            | 5.3  | 3.8 | 20.6| 300 |
| Sulfate ion           | 14.1                | 4.9  | 4.9   | 4.7  | 4.4        | 9.6                                     | 0.7            | 4.9  | 5.7 | 10.7| 100 |
| Dry residue           | 280                 | 37   | 37    | 21.6 | 24         | 54                                      | 18.5           | 22.3 | 45.0| 48.6| - |
| Fe                   | 0.18*               | 0.16 | 0.09  | 0.06 | 0.08       | 0.05                                    | 0.05           | 0.05 | 0.05| 0.16| od |
| Mn                   | 0.03                | 0.02 | 0.02  | 0.03 | 0.03       | 0.02                                    | 0.02           | 0.02 | 0.01| 0.02| - |
| Cu                   | 0.052               | 0.011| 0.003 | 0.003| 0.005      | 0.003                                   | 0.006          | 0.002 | 0.003| 0.002| - |
| Zn                   | 0.075               | 0.013| 0.009 | 0.009| 0.009      | 0.012                                   | 0.006          | 0.003 | 0.004| 0.003| 0.006|
| As                   | <0.0005             | 0.0009| 0.0012| 0.0018| 0.0007    | 0.0016                                  | 0.0010         | 0.0008| 0.0005| 0.0009| - |

Note: * numerator – content of dissolved forms of elements; denominator – content of forms sorbed on suspensions.
Table 3. Volatile Organochlorine Compounds Content in Snow Samples Sampled at the Snow Camp Site and in the Area of Influence, mg/dm³

| Definable ingredients | Industrial platform | west | north | east | South-east | The outskirts of the Semenovskoye village |
|-----------------------|--------------------|------|-------|------|------------|------------------------------------------|
| Tetrachloric carbon   | 0.0004             | <0.0004 | 0.0004 | <0.0004 | <0.0004 | 0.0004 | <0.0004 | <0.0004 | <0.0004 |
| Chloroform            | 0.1000             | 0.050 | 0.0030 | 0.0100 | 0.0040 | 0.0120 | 0.0080 | 0.0020 | 0.0010 |
| Benzole               | 0.0009             | 0.0007 | 0.0010 | 0.0005 | 0.0010 | 0.0008 | 0.0010 | 0.0009 | 0.0006 |
| Bromodichlorom ethane| 0.0020             | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 |
| Dibromochlorom ethane | 0.0005             | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 |
| Toloue                | 0.0009             | 0.0005 | 0.0008 | 0.0010 | 0.0008 | 0.0010 | 0.0010 | 0.0004 | 0.0005 |
| M (p) Xyloans         | <0.0004             | <0.0004 | <0.0004 | <0.0004 | <0.0004 | 0.0005 | <0.0004 | <0.0004 | <0.0004 |
| O, Xyloans. 1,2,4-     | <0.0004             | <0.0004 | <0.0004 | <0.0004 | <0.0004 | 0.0005 | 0.0004 | <0.0004 | <0.0004 |
| Trimethylbenzene 4-    | 0.0005             | <0.0004 | <0.0004 | <0.0004 | 0.0006 | 0.0004 | <0.0004 | <0.0004 | <0.0004 |
| Isopyroiltooluene 1,2- | 0.0016             | 0.0006 | <0.0004 | 0.0010 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | 0.0010 |
| Dichloropropane       | 0.0004             | <0.0004 | 0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 | <0.0004 |

When assessing the snow cover dust content (Table 2), it was found that the content of suspended solids in the snow at a distance of 20 m from the investigated underground leaching block (BPV № 5) in the north, southeast and west directions is quite homogeneous – 34–52 mg/l; in the east direction the dust content is less – 27 mg/l. At the boundary of the sanitary protection zone – in 300 m from the industrial site of BPV № 5 the content of suspended solids in the snow, selected in the north-east, south-east and west directions, was 28–52 mg/l.

The pH of melt water varied in the range of 5.0–5.6 and was in most cases significantly lower than the pH of snow in the settlement. The lowest pH value of 4.2 was found at the industrial site, while pH 4.2–4.5 was found at a point located 20 m east of the BPV No. 5 boundary, in the site with a chlorination unit for productive solutions.

In general, the contamination of snow with inorganic anions and heavy metals is low (Table 2). The content of dry residue and individual ingredients found in snow samples within the sanitary protection zone varies in small ranges without a certain regularity.

Active chlorine in the snow cover is not detected.

To assess the degree of snow cover pollution by water-soluble forms of inorganic compounds, it is possible to use MAC values for fishery water bodies. Since snowmelt water during floods mainly enters surface water bodies, the results can be compared with MACs for fishery bodies. The content of chlorides and sulphates does not exceed MAC. The exception is the content of soluble forms of iron and manganese, which are components of dust particles, which in some points reaches 16 and 3 MACs, copper and zinc – 11 and 9 MACs, respectively.

The level of concentrations of volatile organic compounds present in snow is shown in Table 3. The constant presence of benzene and toluene in all sampled snow samples in comparable concentrations has been established, which allows them to be attributed to the constant natural components of the atmosphere. In contrast, the content of chloroform and carbon tetrachloride decreases with distance from the source of pollution – BPV-5 industrial site. Consequently, chloroform and carbon tetrachloride are marker pollutants of PV production. Apart from the above mentioned organic compounds (tetrachloride carbon, chloroform, benzene, toluene), bromodichloromethane, dibromochloromethane, 1,2,4-trimethylbenzene and 4-isopropyltholuene were
found in the snow cover of the industrial site during the winter period. The most polluted is the northern direction, where tetrachloric carbon, chloroform, benzene, toluene, 1,2,4-trimethylbenzene, 4-isopropyltoluene and the eastern direction (tetrachloric carbon, chloroform, benzene, toluene, xylenes, 1,2,4-trimethylbenzene) were detected in snow with decreasing concentrations as far away from the industrial site.

The formation of aromatic hydrocarbons (benzene, toluene and their substituted ones) is probably related to the transformation of lignin in groundwater [22, 23]. The determinants of the appearance of chlorine and brominated hydrocarbons are both the presence of active chlorine and its substitution by bromine, which is present as an admixture in chlorine [24]. In the snow cover with Semyonovskoe found chloroform, benzene, toluene, 4-isopropyltoluene. The presence of chloroform is a proof of the dispersion of organochlorine compounds from the SP plant at a distance of up to 1 km. Therefore, the SP enterprise affects the atmospheric air of the settlement.

7. Conclusion
The survey of underground water and snow cover in the area of the SP enterprise impact showed that the enterprise has an impact on ground water and atmospheric air during normal operation. The water of observation wells is polluted with specific pollutants, typical for the SP technology.

Snow cover at the industrial site of the enterprise, in sanitary protection and residential areas contains dust, heavy metals, arsenic and some organochlorine compounds, which are components of technological solutions of WP

References
[1] Kutliakhmetov A N, Safarova V I, Shaidulina G F and Nizamutdinova N R 2012 Comparative analysis of environmental safety of various methods of processing gold ores (for example, the Republic of Bashkortostan) Ecol. of urbanized areas 2 49–57
[2] Salikhov D N, Kovalev S G et al 2003 Minerals of the Republic of Bashkortostan (gold) part 1 (Ufa: Ecology) 222 p
[3] Arens V Zh 2001 Physicochemical geotechnology Textbook (Moscow: Moscow State Univer.) 656 p
[4] Melentyev G B, Shelkov E M and Delitsyn L M 2008Prospects of industrial and economic revival and social and ecological rehabilitation of the Moscow lignite basin with the use of the geo-ecological and energy-technological innovations In the coll. Technogenic resources and innovations in technoeconomy (Moscow: OIVTRAKH) pp 27–40
[5] Asalkhanov V A 2005 Development of the advanced oxychloride technology of the gold extraction from the ores with reference to the conditions of the underground leaching Cand. Dissertation thesis (Irkutsk) 17 p
[6] Beletsky V I, Bogatkov L K, Volkov N I et al 1997 Reference book on the uranium geotechnology (Moscow: Energatomizdat) 672 p
[7] Melentyev G B 2009 Innovative technology and new tasks of the technological mineralogy Ecol. of the Russ. Industry 3 14–28
[8] Underground and heap leaching of uranium, gold and other metals Vol 2 Gold 2005 (Moscow: Ore and metals) 328 p
[9] Dokukin Yu V and Samoilov A G 2009 About the efficiency of the gold mining by the underground leaching method Mineral resour. of Russ. 6 49–53
[10] Kazakov P V and Salikhov D N 2006 Mineral resources of the Republic of Bashkortostan (alluvial gold) Part 2 (Ufa: Gilem) 288 p
[11] Reznik Yu N, Timoshenkov S N and Voronov E T 2008 Geotechnological method of the deep gold-bearing placers development on the basis of the chloride hydrometallurgy use Vest. ChitGu 4(49) 122–8
[12] Sedov N P 2008 Optimization of technological parameters of in-situ leaching of precious metals: the example of Dolgiy Mys Cand. Dissertation thesis (Yekaterinburg) 22 p
[13] Zyryanov M N and Leonov S B 1997 Chloride metallurgy of gold (in Russian) (Moscow: JV Internet Engineer.) 288 p
[14] Dokukin Yu V, Savenya N V and Myakotin V V Method of extraction of precious metals from ores Invention patent no 2137855 July 14, 1998 pp 9–14
[15] Fazlullin M I, Avdonin G I and Smirnova R N 2008 To the problem of in-situ leaching of gold Mining Inform. and Analys. Bull. (MIAB), seminar 217 207–17
[16] Glinskiy M L., Glagolev A V., Dorozhko E G., Vetrov V A. et al 2010 Methodical recommendations on the object monitoring of the subsoil condition at the enterprises of the State Corporation “Rosatom” (Moscow: Center for Assist. to Soc. and Environ. Initiatives of the Nuclear Industry) 192 p
[17] Rossman G I, Petrova N E and Samsonov B G 2000 Ecological evaluation of ore deposits (methodological recommendations) Mineral. Raw Mater. 9 150
[18] Timoshenkov S N 2009 Justification and development of effective technology of in-situ leaching of gold from deep alluvial deposits (on the example of South Transbaikalia) Cand. Dissertation thesis (Chita) 23 p
[19] Zabolotskiy A I and Dokukkin Yu V 2009 First experience in the Russian Federation of the commercial gold mining by the underground leaching method from the gold-bearing weathering cords of the Gagarskiy deposit (in Russian) Mining inform.-analyt. Bull. (GIAB) 1 391–402
[20] Fazlullin M I, Shatalov V V, Gurov V A et al 2002 Prospects of the underground in-situ leaching of gold in Russia Non-ferrous metals 10 39–46
[21] Kutliakhmetov A N, Safarova V I, Shaidulina G F et al 2012 Formation and migration of halogen hydrocarbons in natural environments at the underground chloride leaching of noble metals Probl. of reg. ecol. 3 46–53
[22] Orlov D S, Sadovnikova L K and Sukhanova N I 2005 Soil chemistry (Moscow: Higher school) 558 p
[23] Perminova I V 2000 Analysis, classification and prognosis of the humic acids properties Doct. Dissertation thesis (Moscow) 42 p
[24] Vasilieva A I 2006 Influence of chlorination on water quality in the presence of some natural and technogenic impurities Cand. Dissertation thesis (Ufa) 22 p