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ARTICLE

Gold, Mercury, and Silver Extraction by Chemical and Physical Separation Methods

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Abstract: An agitation leaching method was used for gold extraction from Aghdareh mine samples. Mineralogical study showed that 58% of the gold particles were finer than 10 μm. In addition 3% of the grade in the sample was related to refractory gold. Experiments results showed that at the optimum condition gold recovery was 91.8% and silver, and mercury recoveries were 41.5%, and 10.2%, respectively. After performing cyanidation tests for 6 different fractions, it was concluded that the most unleached gold particles exist in the fraction size finer than 25 μm and about 5% of gold particles in the fraction size larger than 25 μm was not leached. Therefore, further comminution was applied which increased by about 3.57% of gold recovery and about 5% of silver recovery. Further comminution did not affect the recovery of mercury. In order to increase the mercury recovery and prevent from amalgamation of gold by mercury particles, Knelson gravity concentrator was used. The tailing of gravity method was examined using cyanidation tests by considering the optimum conditions. According to the final results, using the combination of these methods, gold recovery is increased to 93.3% and the recovery of mercury increased to 42.1% while the recovery of silver is 42.17%, without noticeable change.

Key words: gold; silver; mercury; cyanidation; Knelson method

The recovery of gold can be accomplished via thorough leaching, gravity, flotation, bioleaching, high pressure oxidation, roasting or combination of these methods[1]. Each of these methods strongly depends on the chemical and physical properties of ore, and mineral occurrence state inside the ore[2]. Among these methods, cyanidation is the standard process for the recovery of gold and silver[3]. Cyanidation process due to its high efficiency and cost-effective matter has become the main leaching method for dissolution of gold[2]. The cyanidation reaction for gold and silver occurs according to Eqs.(1) and (2)[4]. Oxidation of gold is a prior process before dissolution of gold within alkaline medium. When gold is oxidized, gold cyano complex $[Au(CN)_2]^-$ is formed with the presence of cyanide[4, 5].

$$4Au + 8CN^- + O_2 + 2H_2O \rightarrow 4[Au(CN)_2]^- + 4OH^- \quad (1)$$

$$4Ag + 8CN^- + O_2 + 2H_2O \rightarrow 4[Ag(CN)_2]^- + 4OH^- \quad (2)$$

The rate of gold dissolution is controlled by a number of parameters including cyanide and oxygen concentration, pH/Eh, particle size, solid-liquid interface, and temperature. Some of the above mentioned factors were investigated in the present work.

Mercury is one the most poisonous elements and its metallic form cannot be removed by chemical reactions or changed into unharmed forms. Mercury is associated with gold mining, and release of mercury into the environment remain a concern due to its health effects on humans and other organisms[6]. Mercury is of paramount importance in the chemistry of gold extraction. Due to its natural occurrence in the form of pure or cinnabar mineral accompanied with gold ores, it is considered an important impurity in the gold cyanidation process. Metallic mercury is capable of adsorbing metallic gold which reduces gold recovery in cyanidation[3]. Mercury strongly follows the chemistry and mechanism of gold cyanidation. According to the Eq.3, in the presence of

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cyanide it is converted to di- or tetra-cyano mercury complex which is highly water soluble. Mercury cyanide complexes compete closely with gold cyanide complexes for adsorption on the active carbons and even can be replaced with some gold cyanide ions on the active carbon [6].

$$4Hg^{2+} + 6CN^- = Hg(CN)_2 + Hg(CN)_4^{2-} \quad (3)$$

Centrifugal separators are not limited to gold but research is also being carried out in coal and hematite processing, as well for processing fine material[7]. Due to the Knelson concentrator capability in the recovery of finer and lager particles of gold, it has been broadly used in the gold extraction industry. Also, it is considered to be a key factor contributing to environmental issues. In gold plants, the gravity method is applied as a pretreatment process which reduces cost of operations[8]. Knelson Concentrators are almost always placed in the grinding circuits [9].

The aims of the present study are to investigate the effective parameters in the cyanidation process, increasing the amount of mercury as a minor product by Knelson concentrator, and finally increasing the recovery of gold.

1 Experiment

The sample was taken from Aghdare mine which is located Takab, Iran. Ore samples with different grades were collected and then mixed with a specific ratio to produce a mean feed grade. This measured value was about 1.5 g/t for Aghdare gold plant. Data show that 150g/t mercury exists in the form of cinnabar mineral inside the ore. Due to the presence of mercury, large portion of gold was lost. Sample size was reduced using cone and cylindrical crushers and ball mill. After comminution stage, 2 kg of homogeneous sample was prepared for leaching tests. Also, some amount of initial sample were taken to do further experiments with Knelson concentrator equipment.

Leaching tests were carried out using a mechanical agitator (Ika-RW20, Germany) within ambient pressure and temperature, inside a 3 liter container with 1 kg ground sample by Denver ball mill. During all experiments, pH of solution was adjusted with pH meter **(**744 Metrohm) to keep constant value of 10.5. Hydrated lime for increasing pH solution and sodium cyanide for dissolution of gold were selected which are currently used in Aghdare gold complex with industrial purity. At the end of each test, pulp was filtered and washed with distilled water. Solution and filter cake were analyzed by atomic adsorption spectrometry and yields were calculated. The most effective parameters on the cyanidation process were identified and optimized including feed size distribution, solid percent, cyanide concentration and time (changing one parameter and keeping constant other parameters at the same time). Finally, response values for gold, silver and mercury recoveries were carefully examined.

Gold and silver particle sizes were in submicroscopic level in Aghdare mine which prevented using of centrifugal method for recovering these metals. Taking into account this fact, Knelson concentrator method for the recovery of cinnabar mineral (density of 8.1 g/cm^3) was chosen. Gravity tests with Knelson concentrator equipment in the laboratory scale (KC-MD-2") were conducted with the bowl capacity of 1 L pulp feed rate of 1 kg/min, and d_{80}=500 μm for feed input (with regard to cinnabar mineral's degree of freedom).

Optical mineralogy (using the prepared polished and thin sections) and X-ray diffraction (XRD) studies were performed to define the main and the trace minerals and their interlocking.

2 Results and Discussion

2.1 Sample characterization and deportment of gold

2.1.1 Sample mineralogy

Main minerals are quartz, Muscovite, calcite, dolomite, and smectite as seen in Table 1. The result of optical mineralogy shows that Aghdare gold particles are mostly distributed as native gold (Fig.1). Amalgamation or electrum grains (gold, mercury, and silver alloys) rarely can be observed inside the ore (Fig.2). It is also found that gold particles are submicroscopic (Fig.3).

Chemical analysis was carried out using atomic absorption spectrometry (AAS). Based on the obtained results, the grades of gold, silver, and mercury in the sample are 1.5, 7.5, and 160 g/t, respectively.

Table 1 Constituents of Aghdare gold ore mine and its gold percentage

Mineral	Formula	Amount/wt%
Quartz	SiO_2	25.7
Muscovite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	10.4
Smectite	$(Ca,Na)_7(AlFeMg)_4[(SiAl)_8O_{20}](OH)_4.nH_2O$	8.6
Kaolinite	$Al_2Si_2O_5(OH)_4$	5.6
Other silicates	-	2.7
Calcite	$CaCO_3$	21.0
Dolomite	$CaMg(CO_3)_2$	9.6
Barite	$BaSO_4$	3.1
Jarosite	$KFe_3(SO_4)_2(OH)_6$	2.0
Lead and iron arsenates	-	2.2
Goethite	FeOOH	3.7
Hematite	Fe_2O_3	1.0
Magnetite	Fe_3O_4	0.3
Pyrolusite	MnO_2	2.5
Anatase-Rutile	TiO_2	0.2
Cinnabar	HgS	0.02
Liberated gold	Au	(226)
Electrum gold	Au<80%+Ag>20%	(8)
Amalgamated gold	Au<80%, Ag+Hg>20%	(9)
Carbonaceous material	C_{org}	0.1

Note: Values inside parenthesis are numbered particles in microscope.

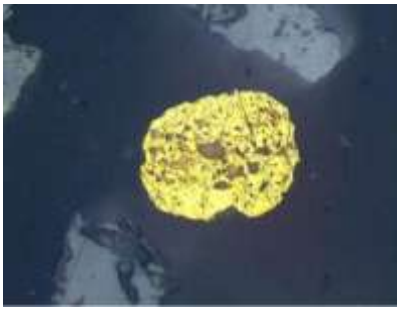

Fig.1 Original gold observation through optical microscopic

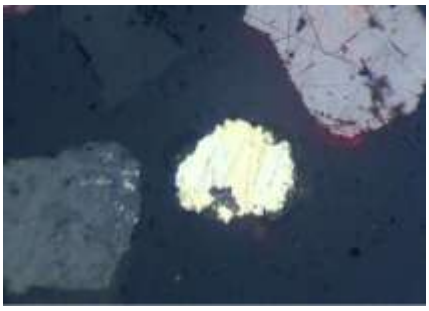

Fig.2 Au-Ag-Hg alloys; electrum [Au, Ag], Au-Ag-Hg amalgams

Fig.3 Enclosed gold in silicate, oxide, arsenate, and sulphide particles in the ore

2.1.2 Deportment of gold in the sample

Gold deportment and occurrence state were examined for the prepared sample in the ore. The results are given in Table 2.

Results show that gold particles finer than 10 μm in Aghdare ore comprise 58% of all gold particles while particles with size greater than 10 μm are inconsiderable. Due to the presence of 3% refractory gold in the ore suggested that using of the UFG (ultra-fine grinding) method for grinding of particles will liberate all gold particles. By applying the UFG method, maximum gold recovery will reach 97% (gold particles show a connection with iron oxide minerals with a formula of FeO_x such as scorodite and jarosite). With regard to the presence of mercury in the ore and also due to the possibility of amalgamation of some liberated gold particles with this element, the recovery tends to decrease practically. Also about 8% of gold particles enclosed in arsenate and iron oxide minerals. For particles finer than 60 μm, 89% of gold particles in the ore share at least one free surface and tend to be leachable.

Table 2 Deportment of gold particles in the sample

State of gold particles in the feed sample	Au amount/ μg g^{-1}	Au particle amount/wt%
Measured grade	1.500	100
Liberated gold particles (>50 μm)	0.0001	-
Liberated gold particles (10~50 μm)	0.003	0.2
Liberated gold particles (<10 μm)	0.863	57.5
Particles with at least one free surface (>50 μm)	0.127	8.5
Particles with at least one free surface (10~50 μm)	0.336	22.7
Gold trapped inside oxides and arsenates (>50 μm)	0.063	4.2
Gold trapped inside oxides and arsenates (10~50 μm)	0.060	4.0
Unleachable particles inside sulfides	0.048	3.2

2.1.3 Gold, silver, and mercury distribution in sample

Gold, silver, and mercury distribution of feed sample after grinding in each fraction are illustrated in Fig.4. The graph reveals that most gold particles in the ore (more than 70%) are finer than 25 μm. Therefore, by UFG method which liberate all gold particles, gold recovery will reach its maximum value of 97%. As shown in graph, silver and mercury distribution is very similar to gold. So we can use all of gold result deportment study for silver and mercury analysis. Also, because there is a considerable amount of gold in each fraction, we cannot recover most of gold particles in feed by gravity methods such as Knelson concentrator.

2.2 Cyanidation study

2.2.1 Effect of particle size on recovery

The effect of feed particle size on the recovery of gold, silver, and mercury was examined. Experiments were conducted using different values of particle sizes in the range of 25~75 μm. In these experiments, other parameters were kept constant including 1000 mg/L of cyanide concentration, pH of 10.5, solid percent of 35%, and leaching time of 24 h. Results are

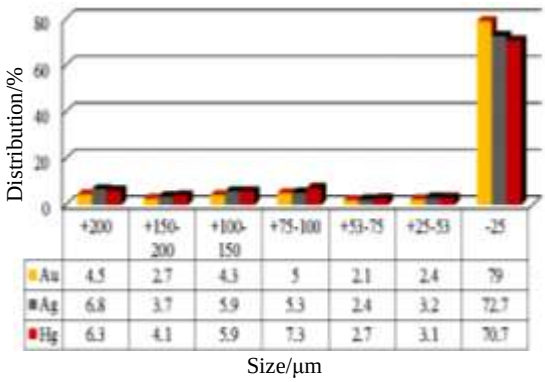

Fig.4 Gold, silver, and mercury distribution percent in each fraction after gridding samples

illustrated in Fig.5 and Fig.6. Based on Fig.5, intensifying of comminution tends to liberate more gold particles which improves the recovery of gold. Optimum particle size is 37 μm when gold recovery reaches 91.9%. However, the obtained results shown in Fig.6 implies that intensifying of comminution will not affect the recovery of silver and mercury. Moreover, because of sulfide phase of mercury and silver leaching, their recovery is very lower than gold leaching recovery.

2.2.2 Effect of leaching time on extraction

In order to determine the optimum leaching time for cyanidation process, an experiment was conducted for 72 h and continually sampling from pulp was done for 2, 4, 8, 24, 48, and 72 h. Results shown in Fig.7 and Fig.8. According to Fig.7, gold dissolution rate is very high for 8 h leaching whereby the recovery of gold reaches 90.5%. From 8 h to 24 h of leaching, gold recovery increases very slowly and then after 24 h it keeps almost a constant value. This may be because the dissolution of gold particles can be liberated or contacted with cyanides at the interface, and later by the dissolution of gold particles surrounded by silicate, oxide other minerals through diffusion. In the current experiment, the recovery of gold after 24 h of leaching is 92.1% which is regarded as optimum leaching time. Moreover, based on our observation in Fig.8, with increasing of leaching time, the recovery of silver and mercury tend to increase.

2.2.3 Effect of solid percent on extraction

In experiment we conducted tests for solid percent in the range of 35%~50%. Based on the results shown in Fig.9 and Fig.10, as solid percent value increases, the recovery of metals

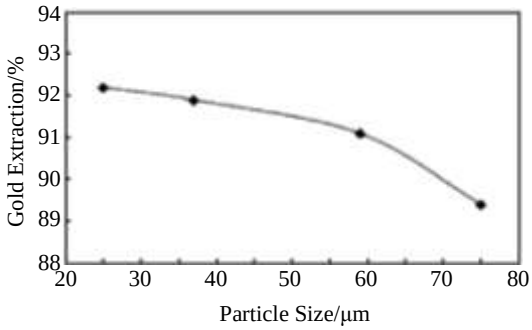

Fig.5 Effect of particle size on gold extraction

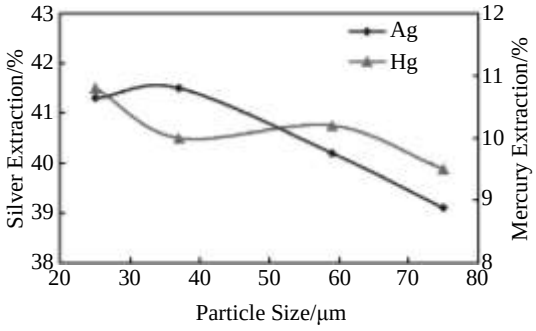

Fig.6 Effect of particle size on silver and mercury extraction

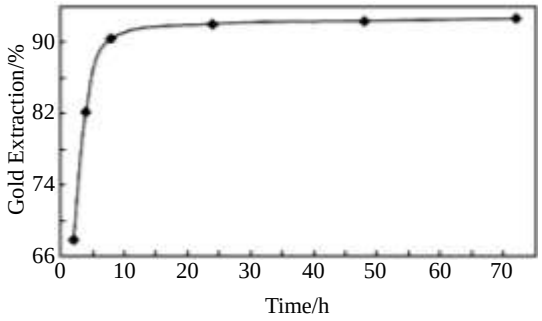

Fig.7 Effect of leaching time on gold extraction

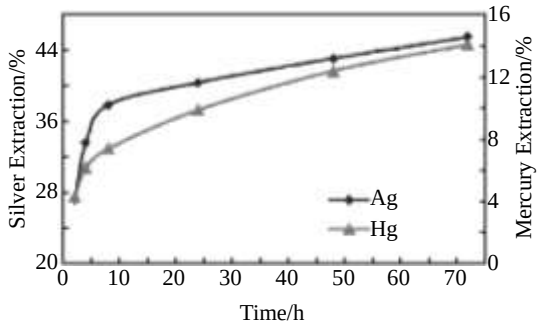

Fig.8 Effect of leaching time on silver and mercury extraction

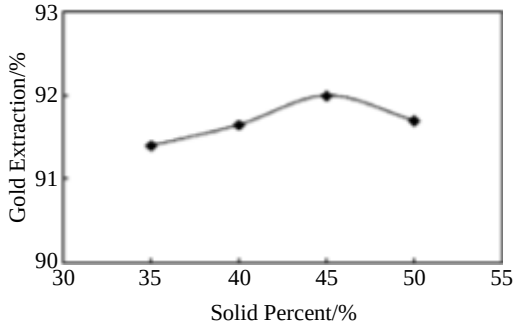

Fig.9 Effect of solid percent on gold extraction

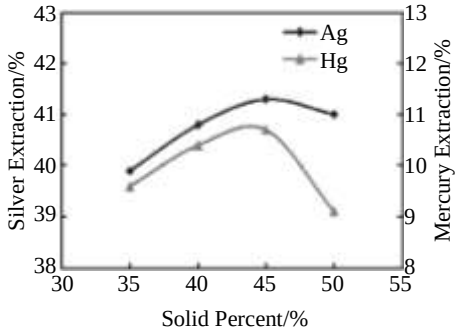

Fig.10 Effect of solid percent on silver and mercury extraction

increases; however, for solid percent greater than 45% the recovery of metals decreases. This is because of high pulp viscosity due to the presence of clay minerals and hydrate slime for adjusting pH of leach medium.

2.2.4 Effect of cyanide concentration on extraction

In order to determine the optimum cyanide concentration, cyanide experiments with various concentrations were done. During the experiment other parameters including particle size, leaching time, and solid percent were kept constant at 37 μm, 24 h, and 45%, respectively. As shown in Fig.11 and Fig.12, increasing of cyanide concentration up to 1200 mg/L is in agreement with an increase in free cyanide ion in leach media. This increases the recoveries of gold, silver, and mercury to and they reach the values of 91.8%, 41.5%, and 10.2%, respectively. Cyanide concentration increase up to 1500 mg/L has no considerable effect on the recovery of gold and silver; however, this reduces the recovery of mercury to about 0.5%. With regard to what we achieved from cyanide concentration experiment, the optimum cyanide concentration is considered to be 1200 mg/L. Around this value, the concentration free cyanide ions inside pulp was measured with about 500 mg/L.

2.3 Leaching tests on each fraction

Six distinct cyanidation tests were conducted for each fraction size. The recoveries of gold, silver, and mercury for each fraction size are given in Table 3. Experiment conditions are as follows: pH of 10.5, leaching time of 24 h, cyanide concentration of 500 mg/L, and sample mass of 300 g. According Table 3, the maximum recovery of gold, silver, and unleached mercury can be obtained for fraction size finer than 25 μm. Also, about 5% of all gold in feed are remained in fraction size greater than 25 μm. Consequently, by regrinding all particles to fraction size finer than 25 μm and liberating valuable minerals we would be able to increase their recovery.

2.4 Ultra-fine grinding (UFG) experiment

In the present experiment, all large particles completely were ground to reach 100% fraction size finer than 25 μm. After blending, a homogenous sample was prepared. Then one specific test conducted by considering exactly previous experiment conditions. Results reveal that under these conditions the recoveries of gold, silver, and mercury become 92.55%, 38.7%, and 13.5%, respectively. It is obvious that further sample grinding improves the recovery of gold by about 5.25% and the recovery of silver by about 5%; however, it does not have a noteworthy effect on the recovery of mercury.

2.5 Combination of Knelson concentrator and cyanidation method

The combination of Knelson concentrator and cyanidation method was carried out in order to improve the recovery of mercury as cinnabar mineral and also increase the recovery of gold during leaching process. In this case, Knelson concentrator tests were applied to determine the optimum pressure of equipment so as to obtain the maximum recovery of mercury in the concentrate and minimum value of grade in the tailing section. Then, Knelson's tailing went through cyanidation operation. According to the results of Knelson's experiments as shown in Fig.13, cinnabar concentrate with the grade value of 39.86% and recovery value of 37% can be achieved at 11 psi (75.85×10^3 Pa) of water back pressure. Moreover, mercury grade in Knelson's tailing is decreased to 53 μg/g. Cyanidation experiments on Knelson's tailing under optimum conditions show that the recovery of gold increases by 1.5%; however, the recovery of silver does not change considerably. Based on the final results, total recoveries of gold, silver and mercury

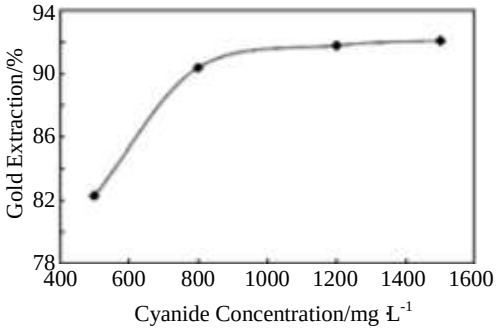

Fig.11 Effect of cyanide concentration on gold extraction

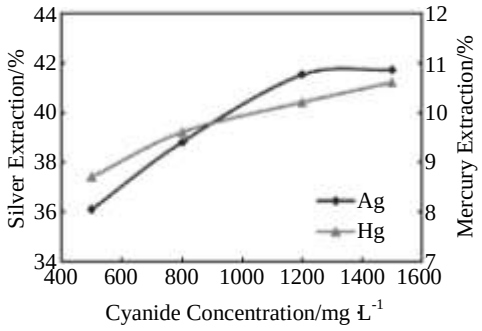

Fig.12 Effect of cyanide concentration on silver and mercury extraction

Table 3 Measured recovery and unleached of gold, silver, and mercury for each fraction size

Fraction size/μm	Au recovery/%	Au unleached/%	Ag recovery/%	Ag unleached/%	Hg recovery/%	Hg unleached/%
200	3.2	1.24	1.6	5.15	0.7	5.5
150~200	2	0.74	0.3	3.34	0.7	3.34
100~150	3.3	1.02	1.4	4.5	0.8	5.11
75~100	3.6	1.36	0.7	4.64	1.1	6.22
53~75	1.7	0.46	0.1	2.3	0.2	2.45
25~53	1.7	0.68	0.5	2.71	0.2	2.88
<25	71.8	7.2	29.1	43.6	10.9	59.7
Sum	87.3	12.7	33.7	66.3	14.6	85.2

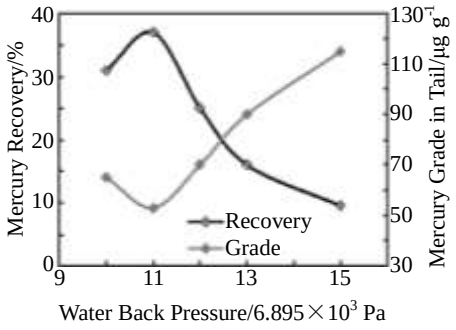

Fig.13 Knelson experiment results for different water pressures

are 93.3%, 42.17%, and 42.16% (37% as cinnabar mineral), respectively, when the combination of two methods applied.

3 Conclusions

1) Gold particles in Aghdare ore are in submicroscopic level. Liberated gold particles finer than 10 μm comprise 58% of all gold particles and gold particles greater than 10 μm have inconsiderable portion in the ore. Also, refractory gold accounts for 3% of the grade. Complete liberation of gold particles in the sample occurred in fraction size finer than 10 μm. A substantial portion of gold particles in the ore (more than 70%) exists in fraction size finer than 25 μm.

2) Optimum conditions for cyanidation experiment are as follows: feed d_{80}=37 μm, cyanidation time of 24 h, solid percent of 45%, and cyanide concentration of 1200 mg/L in constant pH of 10.5. Under these optimum conditions, the recovery of gold, silver, and mercury are 91.8%, 41.5%, and 10.2%, respectively.

3) The maximum unleached gold, silver, and mercury tend to be in fraction size finer than 25 μm. Also, about 5% of all gold particles in the feed are remained in the fraction size greater than 25 μm. Therefore, by further comminution (finer than 25 μm) and liberation of valuable particles, the recovery of gold can increase by 3.57% and the recovery of silver by 5%; however, the recovery of mercury can not be affected.

4) The combination of two Knelson concentrator and cyanidation methods can obtain the total recovery of gold 93.3%, silver 42.17%, and mercury 42.16% (37% as cinnabar mineral). For water pressure of 75.85×10^3 Pa and feed distribution size of 500 μm, the cinnabar concentrate with mercury grade of 39.89% and mercury recovery of 37% can be obtained.

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化学和物理分离法萃取金、汞、银

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摘 要：采用搅拌过滤法对 Aghdareh 金矿样品进行金的萃提。矿物学研究表明，样品中 58%的金颗粒小于 10 μm，该等级的 3%属于难熔金。实验结果表明，在最优条件下，金回收率可达 91.8%，银和汞分别为 41.5%和 10.2%。以氰化法测试的 6 种分次尺寸样品的结果表明，未萃取的金粒子大多小于 25 μm，还有大约 5%的金颗粒大于 25 μm。因此，对样品要进一步粉碎，这样可使金和银回收率分别提高约 3.57%和约 5%，进一步粉碎样品并不影响汞的回收率。采用 Knelson 重力选矿法可提高汞回收率并防止金和汞的混合，利用氰化法检测重力法的尾料。这些方法的结合应用，最终使金回收率达到 93.3%，汞回收率增加到 42.16%，而银回收率没有明显的变化，为 42.17%。

关键词：金；银；汞；氰化法；Knelson 方法

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