



Designing the SART process – A review

Humberto Estay

Advanced Mining Technology Center (AMTC), University of Chile, Av. Tupper 2007, AMTC Building, Santiago 8370451, Chile



ARTICLE INFO

Keywords:
SART process
Cyanide recovery
Gold cyanidation
Gold-copper ores

ABSTRACT

Almost twenty years ago, the first paper about the SART process was published, and eleven years ago the first SART plant was commissioned and operated at Telfer mine, in Australia. Up to this moment, seven SART processes have been constructed and operated in different gold cyanidation plants worldwide, demonstrating the interest of the metallurgical community for this technology. The first pilot testing of a SART process was conducted and published in 1998 for Lobo-Marte project, in order to implement a feasible technology to treat a gold ore containing cyanide-soluble copper. This milestone was the driving force to promote this technology in other mines having the same issue: the high cyanide-soluble copper content in gold ores which limits the profitability of a gold mine project. Currently, the SART process has demonstrated to be the best option to treat gold-copper ores using cyanide, due to its capability to recover cyanide and produce a saleable copper product. As a matter of fact, a SART plant can reduce the operational cost and increase the incomes in a gold mine, although the main achievement is to make feasible the treatment of a gold-copper ore deposit. The aim of this work is to present the state-of-art of the SART process, focused on designing and showing a compilation of published work about different SART projects and plants.

1. Introduction

1.1. Gold ores containing copper

The cyanidation of gold ores, which have copper content, is currently frequent in gold plants. In fact, the cyanide-soluble copper minerals in gold cyanidation plants affect the performance and profitability of the project. In this area, different studies regarding chemistry, treatment and separation processes of these types of ores have been conducted (Shantz and Reich, 1978; Nguyen et al., 1997; Deschênes and Prud'homme, 1997; Coderre and Dixon, 1999; Lu et al., 2002; Breuer et al., 2005; Sceresini, 2005; Dreisinger et al., 2008; Karimi et al., 2010; Kyle and Hefter, 2015; Sceresini and Breuer, 2016). They show that different copper minerals can be present in a gold ore and its dissolution in cyanide can reach values higher than 90% depending on operational conditions and copper mineralogy. For instance, Table 1 shows typical values reported in literature (Shantz and Reich, 1978; Sceresini, 2005; Sceresini and Breuer, 2016) for copper minerals in 0.1% NaCN solutions. These values indicate the capability of copper minerals to be dissolved by cyanide.

On the other hand, copper dissolution in gold cyanidation plants also depends on the particle size of ore, type of operation (heap or agitation leaching), copper grade, leaching time, and on other operational conditions. In this respect, operational values of copper dissolution ranging between 15 and 40% from different heap leaching plants

have been reported (Estay et al., 2013c). These copper dissolution values (see Table 2) are lower than the solubilities presented in Table 1, probably provoked by low copper grades or copper mineral content having low solubility in the ore. These copper dissolution values seem low to cause issues in gold mines. However, the gold cyanidation plants have recirculation flows, especially heap leaching processes, which increase the impurities concentration, as it is copper in pregnant and barren solutions, even when dissolution rates are low. In fact, Bustos et al. (2008), Botz et al. (2011b), and Estay et al. (2012c) used similar copper dissolution values from Table 2 to estimate an equilibrium copper concentration in a typical heap leaching plant, obtaining maximum copper concentration values higher than 2000 mg/L. These results are supported by operational data from gold cyanidation plants which have copper minerals in the ore, such as Gedabek plant (800 mg/L), Yanacocha gold mill plant (1000 mg/L), Telfer (1000 mg/L), and Mastra plant (1500 mg/L) (Estay et al., 2012c; Adams, 2013). The SART process is included in these plants, reducing the copper inventory in the system, so that the copper concentration expected without the SART process must be higher.

The copper behavior in cyanide solutions has been an issue discussed in literature (Izzat et al., 1967; Zhang et al., 1997; Lu et al., 2002; Marsden and House, 2006; Dzomback et al., 2006; Kyle and Hefter, 2015), although there are some differences in the equilibrium constants reported. Copper is present in cyanide solution as Cu^{+1} ion, creating different copper-cyanide complexes, such as $\text{Cu}(\text{CN})_2^-$, Cu

E-mail address: humberto.estay@amtcl.cl.

<https://doi.org/10.1016/j.hydromet.2018.01.011>

Received 1 July 2017; Received in revised form 13 January 2018; Accepted 18 January 2018

Available online 02 February 2018

0304-386X/ © 2018 Elsevier B.V. All rights reserved.

Table 1
Solubility of copper minerals in 0.1% NaCN solutions (Shantz and Reich, 1978; Sceresini, 2005; Sceresini and Breuer, 2016).

Mineral	Formula	Percent total copper dissolved	
		23 °C	45 °C
Azurite	2CuCO ₃ Cu(OH) ₂	94.5	100
Malachite	2CuCO ₃ (OH) ₂	90.2	100
Chalcocite	Cu ₂ S	90.2	100
Covellite	CuS	95.6 ^a	–
Native copper	Cu	90.0	100
Cuprite	Cu ₂ O	85.5	100
Bornite	FeS·2Cu ₂ S·CuS	70.0	100
Enargite	Cu ₃ AsS ₄	65.8	75.1
Tetrahedrite	Cu ₁₂ Sb ₄ S ₁₃	21.9	43.7
Crysocolla	CuSiO ₃ ·H ₂ O	11.8	15.7
Chalcopyrite	CuFeS ₂	5.6	8.2

^a Value obtained from 5.15 g NaCN per g Cu at room temperature.

Table 2
Au and Cu recovery in Heap Leach Projects (Estay et al., 2013c).

Parameter	Project 1	Project 2	Project 3	Project 4
Particle size	80%-1"	80%-3/4"	100%-3/8"	80%-1/2"
Au content, g/t	0.4	0.67	1.51	0.61
Cu content, %	0.05	0.07	0.07	0.04
Au recovery, %	65	55–70	65	81
Cu recovery, %	20	14	39	30
Cu tails, %	0.040	0.058	0.042	0.028

Table 3
Values of equilibrium constants and standard enthalpy change for copper-cyanide species.

Equation	K _i at 25 °C	ΔH _i at 25 °C, kJ/mol	References
HCN ↔ H ⁺ + CN ⁻	6.17 × 10 ⁻¹⁰	43.5	Izzat et al., 1962
Cu ⁺ + CN ⁻ ↔ CuCN(S)	1.0 × 10 ²⁰	128.0	Lu et al., 2002
CuCN + CN ⁻ ↔ Cu(CN) ₂ ⁻	8.71 × 10 ³	-121.8	Izzat et al., 1967
Cu(CN) ₂ ⁻ + CN ⁻ ↔ Cu(CN) ₃ ⁻²	2.0 × 10 ⁵	-46.5	Izzat et al., 1967
Cu(CN) ₃ ⁻² + CN ⁻ ↔ Cu(CN) ₄ ⁻³	3.16 × 10 ¹	-46.9	Izzat et al., 1967

(CN)₃⁻², Cu(CN)₄⁻³, and the solid specie CuCN. Moreover, the speciation of copper-cyanide complexes depends on the copper-cyanide molar ratio and the pH present in the cyanide solution. Lu et al. (2002), and recently Kyle and Hefter (2015) presented critical studies to consolidate a chemical behavior of copper-cyanide complexes, comparing and analyzing the experimental methods used to obtain the values of equilibrium constants. Table 3 shows the values of equilibrium constants and standard enthalpy for copper-cyanide complexes. Thereby, cyanide species distribution has been estimated (Fig. 1) using parameters shown in Table 3. Fig. 1 shows the result of distribution of the cyanide species for a solution with typical operational concentrations in a cyanidation plant containing cyanide-soluble copper minerals. The free cyanide content is around 20% under the simulated conditions for pH higher than 10. When copper concentration rises over 300 mg/L, the free cyanide content decreases under 10%, risking an optimum gold dissolution.

This means the copper-cyanide complexes contained in cyanide solutions could promote different drawbacks in a gold cyanidation plant. These issues are described as follows:

1. Additional cyanide consumption in leaching operation: Cyanide-soluble copper content in the ore will consume additional free

cyanide in the leaching process to form copper-cyanide complexes, according to the operation pH (typically 10–11). The literature has reported additional NaCN consumption around 0.5–4.0 kg/t, depending on the mineralogy, copper grade, and type of leaching operation (MacPhail et al., 1998; Ford et al., 2008; Vargas et al., 2013). These cyanide consumption values can dramatically increase the operational costs in a cyanidation plant.

2. Increasing the cyanide concentration in the leach tails: Cyanidation plants include recycle streams to recover water and cyanide. Nevertheless, these recycle streams increase the inventory of impurities in the cyanide solution, such as copper-cyanide complexes. These recycle flows contain different elements, triggering a deleterious effect on upstream operations (Adams, 2013). Additionally, the steady state condition of the plant operation determines values of species concentration in the entrained solution of leach tails similar to the species concentration in the solutions of the plant (Bustos et al., 2008). Therefore, the concentration of the weak acid dissociable (WAD) cyanide in leach tails could rise over 50 mg/L in cyanidation plants, which is the limit of cyanide code (Logsdon et al., 1999; Mudder and Botz, 2004). This fact might require to include a cyanide destruction operation in gold/copper plants in order to treat leach tails, increasing the operational and capital costs.
3. Decreasing adsorption efficiency: As mentioned above, the only bleed of copper-cyanide complexes are the leach tails, therefore copper concentration in pregnant leach solution (PLS) could rise over 0.5 g/L, increasing the presence of Cu(CN)₃⁻² ion. According to the literature (Sceresini, 2005; Marsden and House, 2006; Dai and Breuer, 2009; Dai et al., 2012), copper-cyanide complexes can be adsorbed by activated carbon in the following order: Cu(CN)₂⁻ > Cu(CN)₃⁻² > Cu(CN)₄⁻³. Hence, high copper concentration with low free cyanide content can promote the presence of Cu(CN)₃⁻², which competes with gold for adsorption area in the carbon, decreasing the efficiency of the gold adsorption. In turn, the gold concentration in the barren solution (BLS) will be higher, increasing gold losses in the leach tails. Finally, this fact will cause a decrease in gold production. In case of zinc precipitation processes (Merrill-Crowe), the copper precipitation could occur, increasing zinc consumption.
4. Contamination of dore metal: The copper contained in the PLS will promote copper contents in the elution solution (carbon adsorption processes) or Merrill-Crowe precipitate (Merrill-Crowe processes) which could contaminate the dore metal, affecting its purity and final price.
5. Wrong measurement of free cyanide: The most common method to measure the free cyanide concentration for a solution in a cyanidation plant is by using silver nitrate titration with rhodamine endpoint. According to literature (Dai et al., 2005; Botz et al., 2011a; Breuer et al., 2011), this method overestimates the free cyanide concentration when copper concentration increases, because part of the cyanide associated to copper in the complex cyanide-copper is measured as free cyanide during the titration. This issue can have a serious impact on the process control, particularly on the regulation of the free cyanide concentration needed for recovering gold in the leaching process.
6. Reduction of ore resources: The above-mentioned issues will increase the operational costs, or decrease gold production, reducing the value of the ore. This fact will reduce the mine resources, affecting the feasibility of a new project or the life of mine in a current operation (Estay et al., 2012c).

1.2. Why use the SART process to treat cyanide-soluble copper ores?

The gold mining industry has solved the inclusion of the SART (Sulfidization, Acidification, Recycling and Thickening) process in the treatment of gold-copper ores, in order to avoid the problems explained

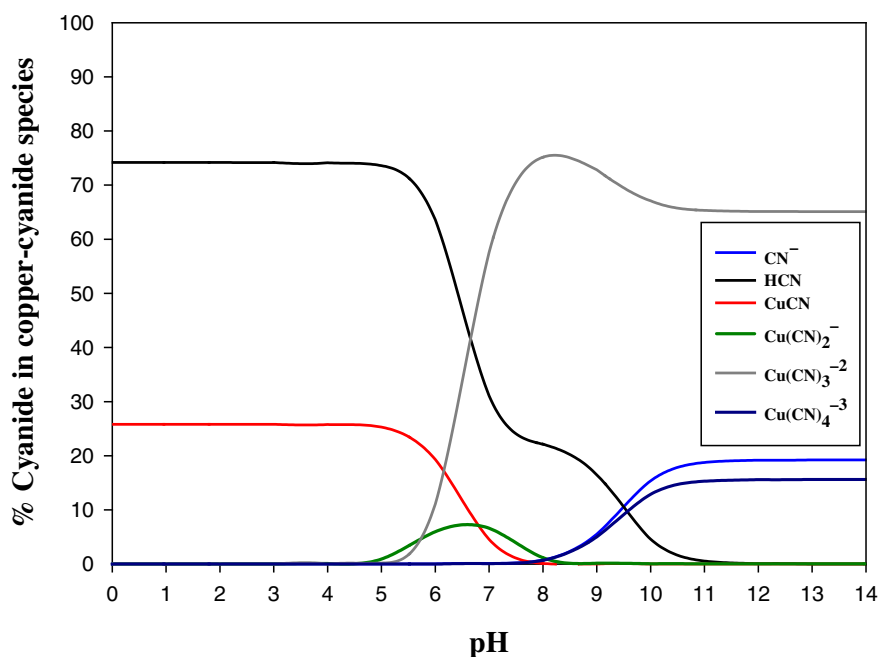
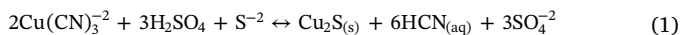


Fig. 1. Distribution of cyanides species for a system containing 250 mg/L Cu and 400 mg/L total cyanide at 15 °C (Estay, 2013).

earlier, and allowing the feasibility to treat minerals containing cyanide-soluble copper species (MacPhail et al., 1998; Barter et al., 2001). The SART process is based on the low solubility of cuprous sulfide (synthetic chalcocite, Cu_2S , $K_{\text{sp}} = 2.3 \times 10^{-48}$), and dissociation of copper-cyanide complexes at low pH to form free cyanide and copper precipitate. In this way, the SART process adds sulfide ion and sulfuric acid in a cyanide solution in order to achieve the following reaction (MacPhail et al., 1998).



In order to obtain a sulfide source, the reagents NaHS, Na_2S and H_2S can be used (Adams et al., 2008). The products (free cyanide and copper precipitate) of the SART process allow the following advantages in a cyanidation plant with high contents of gold-copper ores:

1. Reducing global cyanide consumption in the plant, decreasing operational costs.
2. Increasing the incomes of the plant, due to the generation of a by-product (copper precipitate), which can be sold as copper concentrate.
3. Decreasing copper concentration in solutions, avoiding gold recovery problems, free cyanide measurements issues and reducing the cyanide content in leach tails.
4. The SART process allows the treatment of ores with high copper contents, increasing the profitability of a current operation or making feasible a new project.

The SART process is based on the Metallgesellschaft Natural Resources (MNR) process (Potter et al., 1986). The core of this process (Eq. (1)) is identical to the SART process, although the precipitate handling is different. The MNR process uses only filtration to separate the solid precipitate from the solution, while the SART process has included thickening and recycling stages, achieving advantages in safety and equipment size (Fleming and Trang, 1998; Fleming, 2005, 2016).

MacPhail et al. (1998) published the first study of the SART process, where a pilot plant was run to determine design parameters for LoboMarte project, which finally was not implemented. The main results from this study were copper and cyanide recoveries higher than 95% at pH 3, and 105% sulfide stoichiometric dosage. Later, Barter et al. (2001) performed the second work published about SART process,

developing experimental testwork and pilot plant to define operational parameters for Telfer project (Australia). The results of this work were the design basis for the first SART plant constructed in the world in the Telfer gold mine, commissioned at 2006 to treat 60 m³/h of PLS solution. From Telfer experience, the interest of the gold mining industry in the SART process increased. Hence, the largest SART plant installed in the world, Yanacocha, in Perú, was designed to treat 1400 m³/h, and it was commissioned at 2008. Then, there were other SART plants constructed and operating, such as Lluvia de Oro (Mexico, 340 m³/h, 2008), Gedabek (Azerbaijan, 140 m³/h, 2009), Mastra (Turkey, 120 m³/h, 2010), Maricunga (Chile, 750 m³/h, 2012), and Copler (Turkey, 380 m³/h, 2013). In addition, there are several SART plants projects under study, such as Casino (Canada), Caspiche (Chile), LoboMarte (Chile), and Luiiri (Zambia), among others (Estay et al., 2014a). Nowadays, the SART plants operating and gold projects that include SART process demonstrate the benefits of this technology in a gold mine with high cyanide-soluble copper contents. Fig. 2 shows a timeline with the most important milestones of the SART process development.

1.3. Overview of cyanide recovery processes

The cyanide is a highly toxic reagent that can be lethal to a human being if exposed to high dosages in few minutes (Logsdon et al., 1999). For this reason, the gold mining operates at pH-levels higher than 10.5, in order to minimize the presence of HCN, avoiding risk to personnel and cyanide losses into environment. International regulations and standards establish a maximum HCN concentration in the air of 4.7 ppm, and the WAD cyanide concentration in tailings dam must be lower than 50 mg/L (Logsdon et al., 1999; Mudder and Botz, 2004). In this respect, it should be pointed out that admissible concentrations of cyanide for discharge or bleeding are stricter and depend on each country; however, admissible concentrations are in general lower than 1.0 mg/L. In order to comply with regulations regarding above-mentioned admissible concentrations, it is necessary to include cyanide destruction and/or recovery processes.

The cyanide destruction processes are based on cyanide oxidation to generate cyanate, CNO^- , which is naturally degraded to ammonium and carbonate ions. Typical cyanide destruction processes are alkaline chlorine, INCO process, hydrogen peroxide, Caro's acid, ozone, among others (Botz et al., 2005). The common aspect of all these processes is

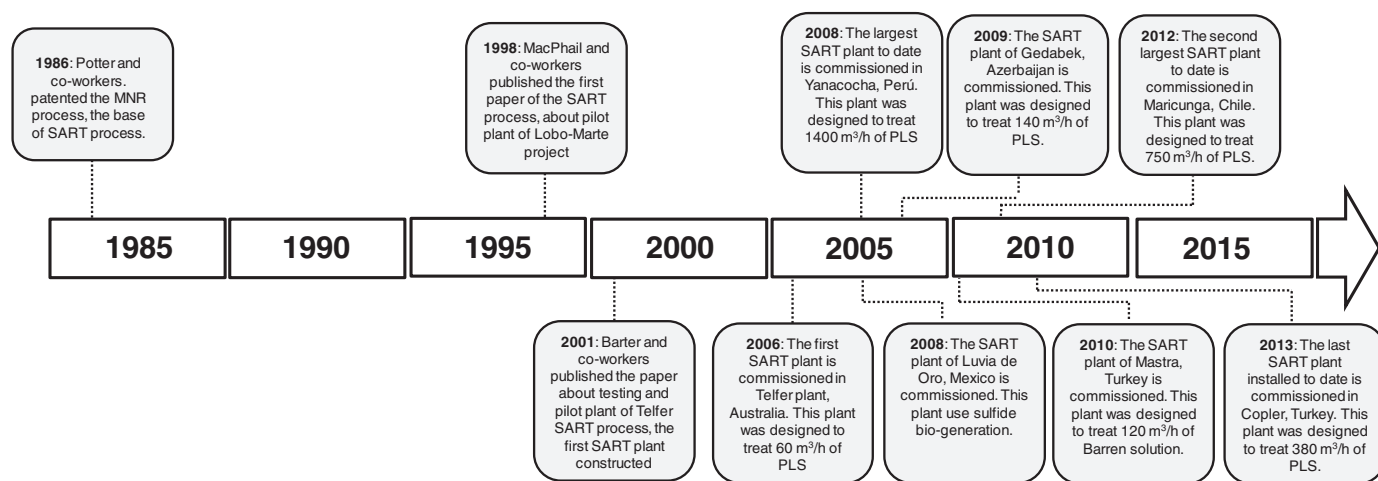


Fig. 2. Timeline of milestones in the SART process's history.

that they use reagents with high oxidation potential which are very efficient but decrease the NPV of a project due to operational costs associated to reagents consumption with no cyanide recovery. For this reason, gold mining industries have shown interest in the implementation of cyanide recovery processes that minimize or avoid the use of cyanide destruction processes, reducing operational costs (Demopoulos and Cheng, 2004). Furthermore, these processes reduce the cyanide consumption, but also decrease the cyanide transport, storage and infrastructure related.

There are several types of cyanide recovery processes in different stages and scales of study (Fleming and Trang, 1998; Fleming, 2005; Adams and Lloyd, 2008; Alonso-Gonzalez et al., 2009; Dai et al., 2012; Kuyucak and Akcil, 2013; Xie et al., 2013; Fleming, 2016). Cyanide recovery processes of acidification that treat clear solution have been set up at industrial scale, such as the SART process (MacPhail et al., 1998) and AVR (Acidification, Volatilization and Regeneration) process (Smith and Mudder, 1991). These technologies are currently installed and operating in gold cyanidation plants, reducing the overall cyanide consumption and providing new opportunities for processing gold ores with high cyanide consumption (Smith and Mudder, 1991; Botz et al., 2004; Botz and Acar, 2007; Estay et al., 2012a; McGrath et al., 2015). These industrial processes are based on the following cyanide dissociation reaction (Marsden and House, 2006).



The logarithmic exponent of the dissociation constant pK_a of HCN at 25 °C is 9.21 (Izzat et al., 1962). Thus, pH values lower than 9.21 promote the presence of dissolved HCN in solution. For this reason, the characteristic processing condition of AVR and SART processes calls for a low pH range (pH < 7.0).

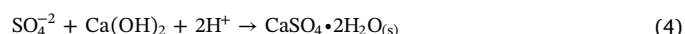
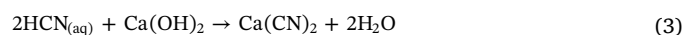
2. Description of the SART process

The SART process was designed to regenerate cyanide from gold cyanidation processes with high cyanide soluble-copper contents. The name SART refers to the core unit operations defining the process: sulfidization (S), acidification (A), recycling of the copper precipitate (R), and thickening of the copper precipitate (T). This regeneration process employs sulfide (Na_2S , NaHS or H_2S) under acidic conditions for the precipitation of copper sulfide (Cu_2S), generating HCN as described in Eqs. (1) and (2). The SART process can achieve copper recoveries above 90% and free cyanide regeneration over 90% using sulfide stoichiometric addition higher than 100% (Botz and Acar, 2007; Ford et al., 2008). Likewise, the SART process is able to precipitate other cyanide soluble-metals present in solution such as silver, zinc, nickel and mercury. The SART process uses thickener and filtration

stages to recover the Cu_2S precipitate, thereby obtaining a filter cake with high solids contents. The clarified solution is neutralized using milk of lime to produce $\text{Ca}(\text{CN})_2$, which increases the pH of the effluent solution. The addition of calcium into the system from lime produces gypsum, which must be removed from the process using thickening and filtration stages.

Fig. 3 presents a schematic block diagram of the SART process. The acidification (pH 4–5) and sulfidization stages are conducted in the precipitation reactor by addition of sulfuric acid (H_2SO_4) and sodium hydrosulfide (NaHS), sodium sulfide (Na_2S) or hydrogen sulfide (H_2S). In this reactor Cu_2S precipitation occurs and HCN is generated.

According to Eq. (2), acidification of the solution promotes breakage of weak metal-cyanide complexes (WAD cyanide), such as those formed with the metals Cu, Zn, Ni, Ag, and Hg. On the other hand, according to Eq. (1) the addition of sulfide results in the precipitation of soluble metal ions in the form of metallic sulfides, such as Cu_2S in the case of copper. Under normal process conditions, the expected Cu precipitation efficiency is in the range of 80 to 90%, where the content of copper in the precipitate may run from 60 to 70%. The solids formed in the precipitation reactor are removed from the process by sequential stages of solid-liquid separations. The reactor discharge feeds a thickener where the concentration of Cu_2S precipitate increases. A fraction of the thickener underflow is recycled into the precipitation reactor to serve as seeds for the Cu_2S precipitate, and to increase the floc size. The remaining fraction of the thickener underflow is neutralized to pH 12 by the addition of soda (NaOH), and then sent to the filtration, washing, and drying stages (if needed). The mixture of the thickener overflow clear solution and the filtered solution create the treated solution. This cyanide solution is sent to a neutralization reactor where lime ($\text{Ca}(\text{OH})_2$) is added to reach pH 10–11. According to Eqs. (3) and (4), lime neutralization produces the conversion of dissolved HCN into calcium cyanide ($\text{Ca}(\text{CN})_2$) and the precipitation of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). The solid gypsum must be removed from the process by sequential stages of thickening and filtration.



Similarly to what is done in the Cu_2S thickener, the gypsum thickener operates by recycling part of the underflow stream. The remaining underflow fraction is sent to a stage of filtration and washing, in order to recover gold and cyanide contained in the solution retained in the filtered cake. The overflow solution from the gypsum thickener, together with the filtered solution, corresponds to the final solution produced by the SART plant. This solution is then recycled to the overall leaching circuit, having all of its cyanide content as soluble Ca

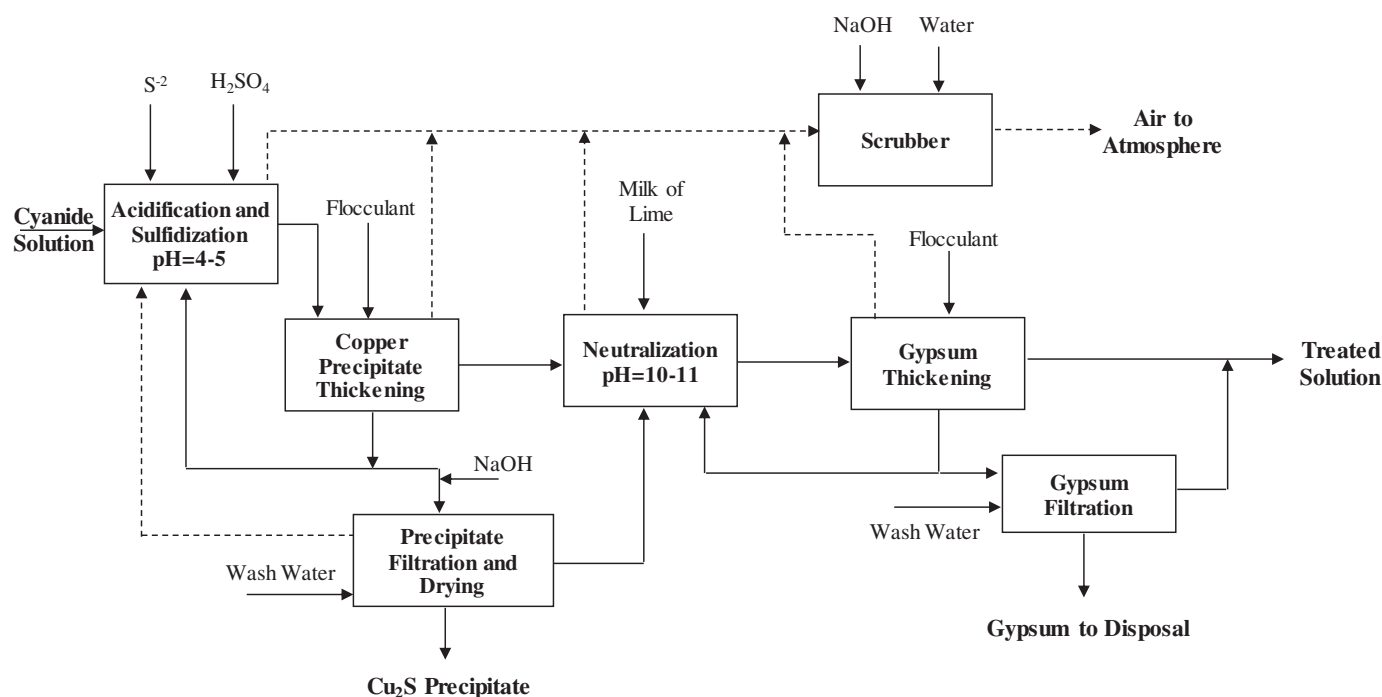


Fig. 3. Schematic block diagram of the SART process (Estay et al., 2012b).

(CN)₂ which is equivalent to free cyanide for the purposes of gold dissolution in the leaching. The gypsum filtration cake, after filtration and washing, is suitably disposed of. The gypsum residue is classified as a non-dangerous residue, which should be deposited on a lined surface to avoid seepage or infiltrations. The process also includes a gas extraction and scrubbing system, connected to the process equipment, in order to capture and treat the eventual emissions of HCN and/or H₂S gases.

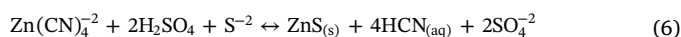
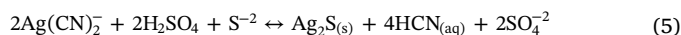
2.1. Chemistry of the SART process

2.1.1. Copper

The SART process is based on reactions from Eqs. (1) and (2), where copper precipitates as synthetic chalcocite, and cyanide complex does so to copper, generating free cyanide (HCN form). The optimum operating conditions will be discussed in Section 4, but literature reports pH values ranging between 3 and 5.5, and stoichiometric sulfide dosage values ranging between 95 and 120% in order to achieve copper recoveries higher than 85% (MacPhail et al., 1998; Barter et al., 2001; Dreisinger et al., 2008; Ford et al., 2008; Botz et al., 2011b; Jimenez-Velasco et al., 2015; Botz et al., 2015). The stoichiometric sulfide dosage is based on Eq. (1), i.e. the sulfide needed to form Cu₂S. However, different authors (Guzman et al., 2010; Simons and Breuer, 2011; Estay et al., 2013b; Simons and Breuer, 2013a,b; Simons, 2015) have reported the presence of CuS (synthetic covellite) and digenite (Cu_{1.8}S) which will be discussed in Section 4. A theoretical model developed by Estay et al. (2013b) suggests the generation of CuS when sulfide addition exceeds 120% stoichiometric. On the other hand, experimental results and operational data from the Telfer SART plant published in different works by Simons and Breuer concluded an oxidation of Cu₂S, forming CuS, even a re-dissolution which produces copper-cyanide complexes, due to the large residence time in thickening operation (Simons, 2015; Simons and Breuer, 2011, 2013a,b). These researchers concluded different hypotheses about sulfide addition, although both recommended further experiments in order to confirm the origin of others copper species. The content of CuS in the copper precipitate will decrease the copper grade of saleable product, although the main impact of this issue is the correct sulfide dosage such that it maximizes the copper recovery,

minimizing reagents consumption.

The SART process has been developed to treat cyanide solutions containing copper, but sulfide ion can precipitate other metal-cyanide complexes such as silver, zinc, among others (Lewis, 2010). Eqs. (5) and (6) show the reactions involved for silver and zinc in the SART process.



2.1.2. Silver

Silver can be frequently present in cyanide solutions. In fact, gold mine production includes silver product in dore metal. Particularly, Yanacocha and Gedabek plants are examples of cyanidation processes which have important silver contents in the cyanide solution feeding the SART process. The Yanacocha SART plant treats PLS containing silver concentrations ranging between 5 and 35 mg/L, obtaining silver recoveries higher than 95%, and silver grades in the precipitate ranging from 5 to 27% (Guzman and Acosta, 2009; Guzman et al., 2010; Vargas et al., 2013). On the other hand, the Gedabek SART plant treats PLS containing about 5 mg/L of silver, obtaining a silver recovery around 95% with silver grades in the precipitate ranging between 1500 and 4000 g/t (Estay et al., 2012a; Hedjazi and Monhemius, 2014). The high silver recovery value is explained by the stability of silver sulfide, even at pH values from 10 to 3 (Simons et al., 2015). Therefore, silver content in the precipitate will increase the sale price of this product, although the silver incomes could be less compared to the dore metal price.

2.1.3. Zinc

Sulfidization of zinc in cyanide solutions was performed in Velardena mine in Mexico, where the barren solution produced in the Merrill-Crowe process was treated with sulfide keeping the pH of operation, in order to obtain free cyanide and ZnS. Thus, the recovered cyanide was used in leaching process and ZnS was mixed with leach tails (Fleming and Trang, 1998). In this context, the SART process could be implemented in a Merrill-Crowe plant to recover cyanide, zinc precipitate as saleable product and reduce the WAD cyanide concentration

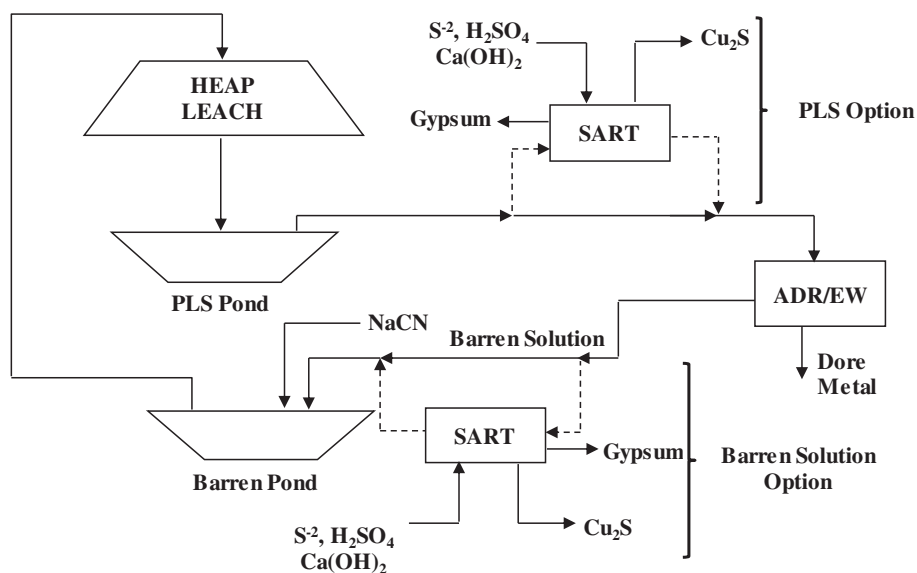


Fig. 4. SART process integration in a heap leaching plant (Estay et al., 2010).

in the plant. Zinc recovery in the SART process has been assessed by different authors (Littlejohn et al., 2013; Sanguinetti et al., 2014; Simons et al., 2015; Baker et al., 2017), obtaining zinc recoveries higher than 95% when sulfide dosage is added in excess, and pH value is above 5. When pH decreases, ZnS is re-dissolved (Simons et al., 2015). This application to the SART process must be studied for each case, because copper contents could contaminate the zinc precipitate, although there are opportunities to precipitate selectively the zinc and copper separately.

2.1.4. Gold

In the case of gold, the expected behavior is that precipitation should not occur, although the literature reports contradictory data. Guzman et al. (2010) reported gold precipitation when pH decreases under 4, reaching values around 20% of gold precipitation for pH 2.5. Additionally, gold precipitation increases when sulfide stoichiometric dosage has increased over 120%. On the other hand, Littlejohn et al. (2013) reported gold precipitation values lower than 1.5% at pH 4.5. Besides Dreisinger et al. (2008) reported gold precipitation values around 20–30% at pH 4–5, and sulfide stoichiometric dosage around 100%. In order to establish an explanation, Simons (2015) developed experiments that report gold precipitation values around 10%, suggesting a co-precipitation/adsorption effect at pH higher than 4. In turn, gold precipitation will increase around 50% at pH 2–3 in presence of silver, forming Ag_3AuS_2 . Furthermore, data from literature does not show evidence of gold precipitation at typical pH values (4–5) of the SART process (Botz and Acar, 2007; Ford et al., 2008; Botz et al., 2011b; Hedjazi and Monhemius, 2014), although they report gold contents in the final precipitate. These results agree with Simons' (2015) suggestion, where gold could have been co-precipitated, adsorbed or entrained by copper precipitate in the range of pH values between 4 and 5. Hence, the location of the SART process in the cyanidation plant must evaluate this fact and it should also consider a washing stage in filtration (which will be discussed in further sections). Additional research must be developed in order to establish the gold department in the SART process.

2.1.5. Others elements

Elements such as nickel, cadmium, lead, arsenic, to mention a few, could also be precipitated in the SART process, although there is few data available in literature. Simons (2015) found nickel precipitation values lower than 20% depending on sulfide addition, and iron (II) precipitation at pH values below 4, forming $\text{Cu}_4\text{Fe}(\text{CN})_6$. Also, Simons

(2015) reported co-precipitation/adsorption of iron (III) reaching precipitation values around 5–8%. Arsenic precipitation in the SART process has been reported by Lopez et al. (2014), who obtained arsenic precipitation values ranging between 10 and 50% at pH 4. Finally, the sulfidization chemistry (Lewis, 2010) indicates that molybdenum, cadmium, lead, among others, could also precipitate in the SART process. Further studies must be performed in order to determine recovery values, conditions and effects in the whole SART process.

2.2. The SART process integration in cyanidation processes

The inclusion of the SART process in gold cyanidation plants depends on the type of cyanide recovery process and the solutions circuit in the cyanidation plant. The SART process returns recovered cyanide in the same treated solution, differently from the AVR process, which returns recovered cyanide in a small volume of solution having a high cyanide concentration. This fact determines the location of the SART process in the process flow diagram of a cyanidation plant.

2.2.1. Heap leaching process

The SART process has been successfully implemented in heap leaching processes, where barren solution is fully recirculated. In this context, the SART process can treat a part of PLS or barren solution (BLS) in a heap leaching plant (Bustos et al., 2008; Ford et al., 2008; Estay et al., 2010; Kratochvil et al., 2013). In both cases, the free cyanide generated will report to the irrigation solution to be consumed in the leaching process. Fig. 4 shows a typical heap leaching circuit (heap leaching, carbon adsorption/desorption (ADR), electrowinning (EW)) and the alternative options to incorporate the SART process.

Processing PLS solution rather than barren solution in the SART plant increases the free cyanide concentration in the ADR feed solution, raising the CN^-/Cu^+ ratio and thus, reducing copper adsorption onto the activated carbon and the cycle time of cold elution. When PLS solution is treated in the SART plant, the washing of the cakes filtered must be optimized in order to minimize gold losses in the entrained moisture. The main risk of this operational option is the eventual drag of gypsum into the carbon adsorption stage (Bustos et al., 2008; Guzman and Acosta, 2009; Estay et al., 2010). Finally, the risk of gold precipitation must be evaluated and reduced by a rigorous pH control.

Processing the barren solution in the SART plant eliminates the risk of gypsum contamination in the carbon adsorption stage. It also conveys the possibility of combining the SART and AVR processes (Bustos et al., 2008), which would make possible the final washing of the heaps

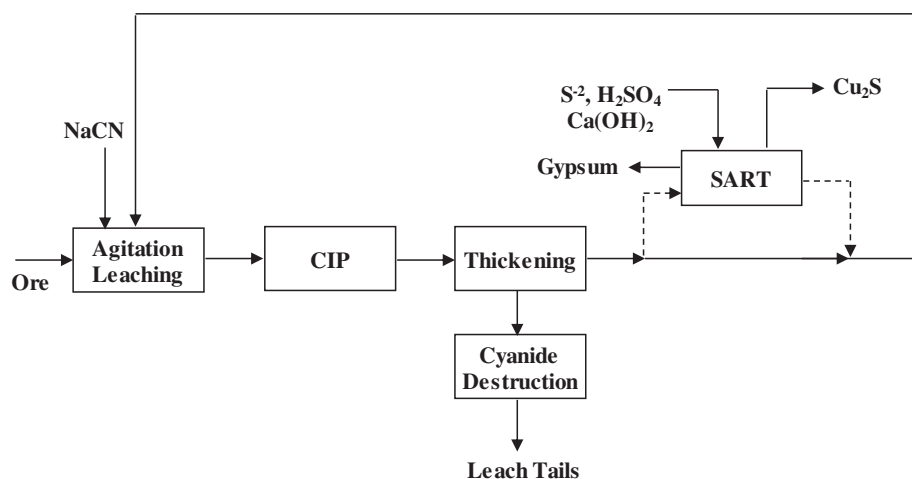


Fig. 5. SART process integration in agitation leaching/CIP plant.

and the reduction of the cyanide contents in the tails moisture. The final selection of the connection point of the SART process with the overall circuit will depend on the solution circuit in the plant, the solution characterization, and the specific local advantages that the process may provide.

2.2.2. Agitation leaching/CIP-CIL processes

Agitation leaching processes which have CIP-CIL operations discharge leach tails as slurry or filtration cake, depend on the final solid-liquid separation process included in the circuit. In both cases, the cyanide solution obtained from these operations is recirculated to milling or leaching. On the other hand, the SART process cannot treat slurries, due to the limitation of recovering the copper precipitate. This limitation forces to include a destruction process to treat leach tails slurries (or cakes) in the CIP-CIL processes, losing part of cyanide and copper contained in the solutions. Hence, the SART process can be integrated in the barren solution recirculated to milling or leaching, as shown in Fig. 5. Melashvili et al. (2015) proposed an interesting modification to this flowsheet to maximize the overall cyanide recovery in a CIP/CIL cyanidation plant. Their approach considered the replacement of a thickening step by a counter current decantation (CCD) circuit, and the treatment of the solution produced by the SART plant through an AVR process to concentrate the recovered cyanide. Thus, the cyanide contained in the leach tails is minimum.

2.2.3. Agitation leaching/Merrill-Crowe (MC) process

The SART process can be implemented to treat cyanide solutions in a Merrill-Crowe (MC) plant to recover zinc and copper. A typical MC process includes different washing stages to recover gold and silver from solutions. This fact complicates the integration of a SART process, because the barren solution is mainly used as washing solution. If the SART process is implemented in PLS or barren solution, the recovered cyanide solution will not be used in the leaching stage, losing free cyanide in tailings. In this context, the SART process must be implemented along with cyanide recovery processes, which can recover cyanide in a small solution to send it into leaching. The available recovery processes capable of recovering cyanide in a small solution are AVR and gas filled membrane absorption (GFMA) processes (Estay et al., 2013a). Therefore, the SART process can be applied coupled with AVR or GFMA process (SART/AVR or SART/GFMA). In general, AVR or GFMA process can treat the thickener overflow of the SART process, recovering cyanide in a small solution (Botz and Acar, 2007; Bustos et al., 2008; Estay et al., 2010; 2014b; Adams, 2013; Kratochvil et al., 2013). Fig. 6 shows a typical agitation leaching/MC process with SART/AVR alternatives of implementation. The leaching processes shown are typical representations of these circuits: albeit the flow diagram for each plant is different, a particular analysis for each case

must be implemented.

2.3. Unit operations options in the SART process

The unit operations of the SART process can vary according to plant requirements or opportunities. Also, there are a few definitions depending on each specific case. In this context, Fig. 3 shows the complete SART process version, which includes copper precipitate filtration, drying stages, and gypsum filtration. These unit operations can be omitted when the whole cyanidation plant presents certain opportunities.

2.3.1. Filtration and drying of copper precipitate

When a gold plant includes a flotation process, the copper precipitate produced by the SART process can be mixed with the whole copper concentrate. An example of this option is the Telfer SART plant, which sends the copper precipitate produced directly from thickener underflow into flotation plant (Barter et al., 2001; Simons and Breuer, 2013b). The main question about this option is the cyanide content in the final copper concentrate. In this context, the ratio of copper precipitate and copper concentrate flows must be evaluated, in order to minimize the cyanide content in the final copper concentrate.

On the other hand, the final moisture content obtained by filtration stage is higher than 40% (Ford et al., 2008; Estay et al., 2010), so that the final price should be penalized. Hence, the presence of drying stage should be evaluated according to the moisture requirements by smelting buyer.

2.3.2. Filtration of gypsum

When a gold plant includes a tailing dam, the gypsum slurry produced by the SART plant can be mixed with tailings. Examples of this option are Yanacocha, Telfer, and Mastra, which send the gypsum slurry produced from thickener underflow into the CCD circuit or tailing dam (Guzman and Acosta, 2009; Simons and Breuer, 2013b; Kratochvil et al., 2013).

2.3.3. Filtered solution from copper precipitate

The solution produced by copper precipitate filtration can be sent into the neutralization reactor or into the precipitation reactor as shown in Fig. 3. The final definition must be outlined estimating the additional recovery and acid consumption produced by recycling into the precipitation reactor. If the income produced by the additional copper recovery is higher than the cost produced by the additional acid consumption, the best option is to recycle the filtered solution into the precipitation reactor.

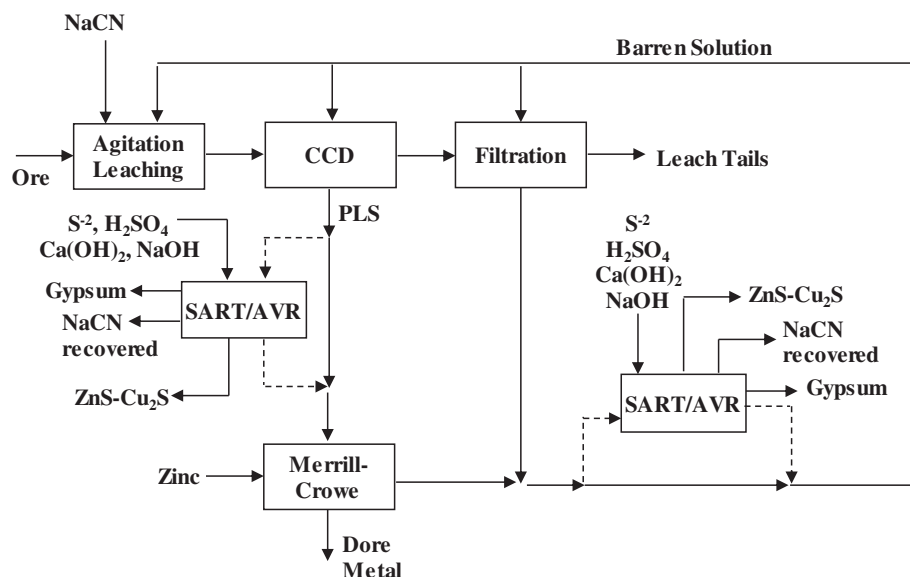


Fig. 6. SART/AVR or SART/GFMA process integration in agitation leaching/Merrill Crowe plant.

2.4. Flowsheet options for SART according to the cyanidation process

From Sections 2.2 and 2.3, one can note that the definition of unit operations and the final position of the SART process in a cyanidation plant are related. Table 4 shows a comparative analysis of different cyanidation process options. In general terms, the SART process can reduce unit operations in agitation leaching processes, because gypsum slurry can be mixed with leach tails. On the other hand, the inclusion of copper precipitate filter and drier is conditioned by the location of a nearby concentrate plant and the moisture requirement of the refinery for precipitate, respectively.

Likewise, the inclusion of a SART process to treat a barren solution is the best option rather than the treatment of PLS. This solution has been also proposed by Kratochvil et al. (2013).

3. Aspects of design

3.1. Definition of the plant capacity

The main objective of the SART process is to reduce the copper concentration in a cyanidation plant by causing a bleed of copper in the whole process. The latter can be achieved by treating a part or the total flow that contains the metal-cyanide contents, as shown in Figs. 5 and 6. The cyanidation processes shown in these figures include recycled flows in order to keep the water balance. For these types of cyanidation processes, a steady-state mass balance of copper (or another interest metal, such as zinc) can be performed to determine the SART plant capacity required to keep the copper concentration below a certain copper concentration value, as shown in Eq. (7) (Bustos et al., 2008).

$$\frac{tL_{Cu}D_{Cu}}{24 \cdot 100} = F_{SART}\eta_{SART}[Cu]_f + \frac{tH_f}{24}[Cu]_f \quad (7)$$

where t is the ore fed into the cyanidation plant (t/day), L_{Cu} is the copper grade in the ore (kg/t), D_{Cu} is the dissolution rate of copper (%), F_{SART} is the SART plant capacity (m^3/h), η_{SART} is the copper precipitation efficiency expected in the SART process (%), $[Cu]_f$ is the copper concentration in cyanide solution when steady-state is reached (kg/m^3) and H_f is the final moisture of leach tails (m^3/t). Thus, a curve of copper concentration in steady-state respect to the SART plant capacity, represented as a fraction of total flow from the cyanidation plant, can be performed using Eq. (7), as shown in Fig. 7 (Bustos et al., 2008; Estay et al., 2010, 2012c).

The steady-state analysis can be useful for agitating leaching plants.

Nevertheless, the heap leaching process can reach the steady-state after months or years, due to the long leaching cycle required by this process. In this respect, a dynamic mass balance of the heap leaching plant is recommended in order to estimate the SART plant capacity, since steady-state estimation can overestimate the maximum copper concentration values and fails regarding the specific date when the SART plant is necessary (Becker et al., 2012). Hence, studies to determine the SART plant capacity required in a heap leaching plant have been developed using dynamic mass balances, e.g. the Copler SART plant project, where the dynamic simulation estimated a peak of copper concentration around 1800 mg/L for the SART plant capacity of $0 m^3/h$, 800 mg/L for $100 m^3/h$ and 200 mg/L for $300 m^3/h$, as shown in Fig. 8 (Botz et al., 2011b). This study also determined the suggested start date for the SART plant. Likewise, operational results from SART plants installed demonstrate the effect of this process in the copper concentration profile, showing a gradual fall of the copper concentration when the SART process has started to operate (Lawrence and Lopez, 2011; Estay et al., 2012a; Kratochvil et al., 2013).

On the other hand, the SART plant capacity for the cyanidation plants operating in open circuit (with no recycling) requires an alternative analysis considering the final destination of the treated solution, such as the case of the Yanacocha plant, when the SART process treats the whole PLS available (Guzman and Acosta, 2009; Guzman et al., 2010; Vargas et al., 2013; Botz et al., 2015).

3.2. Acidification and sulfidization stage

3.2.1. Effects of acid dosage and pH

The sulfidization reaction described by Eq. (1) is based on the low solubility of the cuprous sulfide generated. In this regard, theoretical estimations have been conducted in order to establish the optimum operational value of pH and support the experimental and operational data published (Estay et al., 2013b; Jimenez-Velasco et al., 2015; Simons, 2015). These studies show the presence of Cu_2S below pH 6, increasing its predominance over 80% when pH value is < 5 . However, the predominance of Cu_2S below pH 5 depends on the sulfide dosage. Thus, $CuCN$ is present when sulfide dosage is $< 100\%$ stoichiometric, and CuS , $Cu_{1.8}S$ and $CuCNS$ species may be present, depending on sulfide dosage, pH, oxygen content and CN/Cu ratio (Estay et al., 2013b; Simons, 2015; Fleming and Melashvili, 2016).

On the other hand, experimental and pilot test-works have been performed in order to determine the optimum pH (MacPhail et al., 1998; Barter et al., 2001; Botz and Acar, 2007; Dreisinger et al., 2008;

Table 4
Flowsheet options of the SART process for different cyanidation plants.

	Heap leaching - BLS	Heap leaching - PLS	Agitation leaching/CIP	Agitation leaching/MC-BLS ^b	Agitation leaching/MC-PLS ^b
Inclusion of copper precipitate filter	Only when does not exist a concentrate plant	Only when does not exist a concentrate plant	Only when does not exist a concentrate plant	Only when does not exist a concentrate plant	Only when does not exist a concentrate plant
Inclusion of copper precipitate drier	Depending on the moisture content required by refinery	Depending on the moisture content required by refinery	Depending on the moisture content required by refinery	Depending on the moisture content required by refinery	Depending on the moisture content required by refinery
Inclusion of gypsum filter	Always	Always	Can be omitted sending the gypsum slurry to leach tails	Can be omitted sending the gypsum slurry to leach tails	Can be omitted sending the gypsum slurry to leach tails
Minimum [Cu] in feed solution, mg/L ^a	Defined by an economic limit and operational performance	Defined by an economic limit and operational performance	Defined by an economic limit and operational performance	Defined by an economic limit and operational performance	Defined by an economic limit and operational performance
Advantages	Avoid possible carbon contamination with gypsum	- Reduces the copper adsorption onto the carbon. - Eliminates contaminants which affect dore quality, e.g. Hg. - Possible contamination of carbon with gypsum. - Silver precipitation, reducing incomes due to silver quality.			
Drawbacks	-	-	-	-	Possible contamination of the gold precipitate with gypsum in gold cementation process

^a Explained in Section 7.

^b The Agitation leaching/MC option must always consider a SART/AVR configuration.

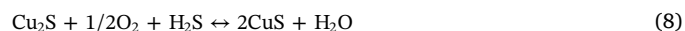
Ford et al., 2008; Botz et al., 2011b; Simons and Breuer, 2011; Lopez et al., 2014; Jimenez-Velasco et al., 2015; Simons et al., 2015; Simons, 2015; Fleming and Melashvili, 2016). Fig. 9 shows data collected from the above publications about copper recovery respect to the pH and sulfide stoichiometric dosage (based on copper), demonstrating that copper recovery increases over 90% when pH is kept below 5.5 at sulfide stoichiometric dosage higher than 100%. This graph was constructed using data from different cyanide solution characterizations, therefore some results are affected by the concentrations of other cations consuming sulfide, such as arsenic, zinc, iron or nickel.

In the same way, the operational results reported in literature for different SART plants support the experimental values discussed earlier, as shown in Table 5. Hence, the experimental and operational data support a recommended pH value ranging between 3.5 and 5.5 to obtain copper recoveries higher than 90%.

As explained so far, the reduction of pH in the SART process is relevant to reach profitable copper and cyanide recoveries. Nevertheless, the consequent acid consumption must be correctly estimated for purposes of design and economical estimation of SART processes. The acid consumption is typically proportional to the WAD cyanide contained in the cyanide solution, depending on the stoichiometric relation of Eq. (1), where the acid consumption is 1.88 kg acid/kg cyanide. Consequently, the data reported in literature (MacPhail et al., 1998; Barter et al., 2001; Botz and Acar, 2007; Ford et al., 2008; Dreisinger et al., 2008; Botz et al., 2011b; Estay et al., 2012a; Lopez et al., 2014; Botz et al., 2015) is slightly above the stoichiometric relation. This fact can be explained by the final pH set, the CN/Cu ratio, and the carbonate content in the feed solution. The excess of free cyanide is consumed by acid, as shown in Eq. (2), and dissolved carbonate consumes acid to form carbonic acid (Simons, 2015). Therefore, the acid consumption must be determined by preliminary experimental studies using real cyanide solution or a synthetic cyanide solution similar to the real or projected cyanide solution, which will be treated by the SART process.

3.2.2. Effect of sulfide dosage in the copper recovery

The sulfide anion allows to generate a metal-sulfide precipitate in the SART process. The first publications suggested sulfide stoichiometric dosages around 95–100% to avoid excess of sulfide that could form CNS⁻ and/or H₂S (MacPhail et al., 1998; Barter et al., 2001). Nevertheless, the following works (see Fig. 9 and Table 5) have demonstrated that sulfide stoichiometric dosages between 110 and 120% reach copper recoveries higher than 90%. The main difference can be explained by the presence of others cations in the cyanide solution, which consume sulfide in the last works, i.e. the first two works assessed cyanide solutions with low additional cations content. Therefore, the sulfide stoichiometric dosage will depend on the cyanide solution characterization, although sulfide stoichiometric dosages higher than 120% do not necessarily ensure an increase in copper recovery, due to a possible formation of copper species with high sulfide content, such as covellite (CuS) and digenite (Cu_{1.8}S). This fact has been reported in literature supported by theoretical approaches (Estay et al., 2013b; Simons, 2015), experimental work (Simons, 2015; Fleming and Melashvili, 2016), and operational analysis in the Yanacocha and Telfer SART plants (Guzman et al., 2010; Simons and Breuer, 2013b). In this context, Simons (2015) suggested that the excess of sulfide can contribute to oxidation of Cu₂S into CuS for long residence times (considering the precipitation reactor and thickening stage), according to the following equation:



Notwithstanding, Fleming and Melashvili (2016) proposed a sulfide stoichiometric dosage avoiding the excess of sulfide, based on their experimental results showing that the excess of sulfide can affect the solid precipitate characteristics of the settling and filtration stages, due to the adsorption of sulfide species (H₂S, HS⁻ and S⁻²) onto the surface of the metal sulfide precipitate. This work presents copper recoveries

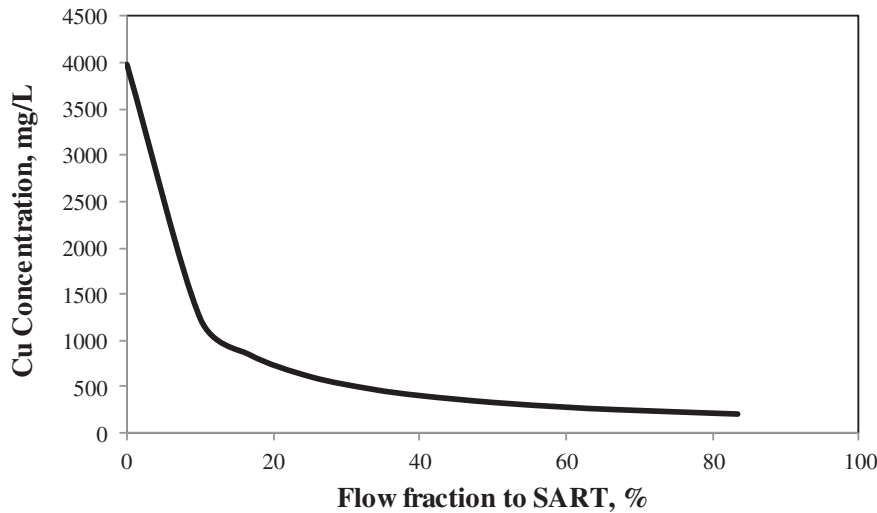


Fig. 7. Typical curve of copper concentration respect to the flow fraction of a heap leach cyanidation plant (Fig. 4) treated by the SART plant, performed by using a steady-state analysis (Estay et al., 2010).

higher than 95% for sulfide stoichiometric dosages of 104%, keeping the pH value in the range of 3.6–4.0. These experimental results are promising, due to the potential reduction of sulfide consumption, although it should be ratified assessing different cyanide solution characterizations and a wide range of values for pH and sulfide dosages.

To sum up, the sulfide stoichiometric dosage must be determined by preliminary experimental work for design purposes, using real or synthetic cyanide solution which simulates the expected cyanide solution characterization, testing pH values from 3.5 to 5.5 and sulfide stoichiometric dosages from 90 to 140%, focused on defining an optimum range, considering reagent costs, copper and cyanide prices, and the impact on the settling and filtration rates.

3.2.3. Effect of the presence of other elements

As mentioned before, the presence of other elements in the cyanide solution fed into the precipitation reactor increases the sulfide consumption, particularly the presence of zinc and silver. In the case of silver, experimental studies demonstrate the generation of Ag_2S according to Eq. (5), with silver recoveries close to 100% at pH values ranging from 10 to 3.0, and sulfide stoichiometric dosages based on copper above 40% (Simons et al., 2015; Simons, 2015). These works also show an effect on the copper recovery at sulfide stoichiometric dosages of 100% based on copper, because the Ag_2S specie is more stable than Cu_2S , therefore the presence of silver forces to operate with sulfide stoichiometric dosages higher than 100%. These experimental results are supported by operational results reported for the Yanacocha

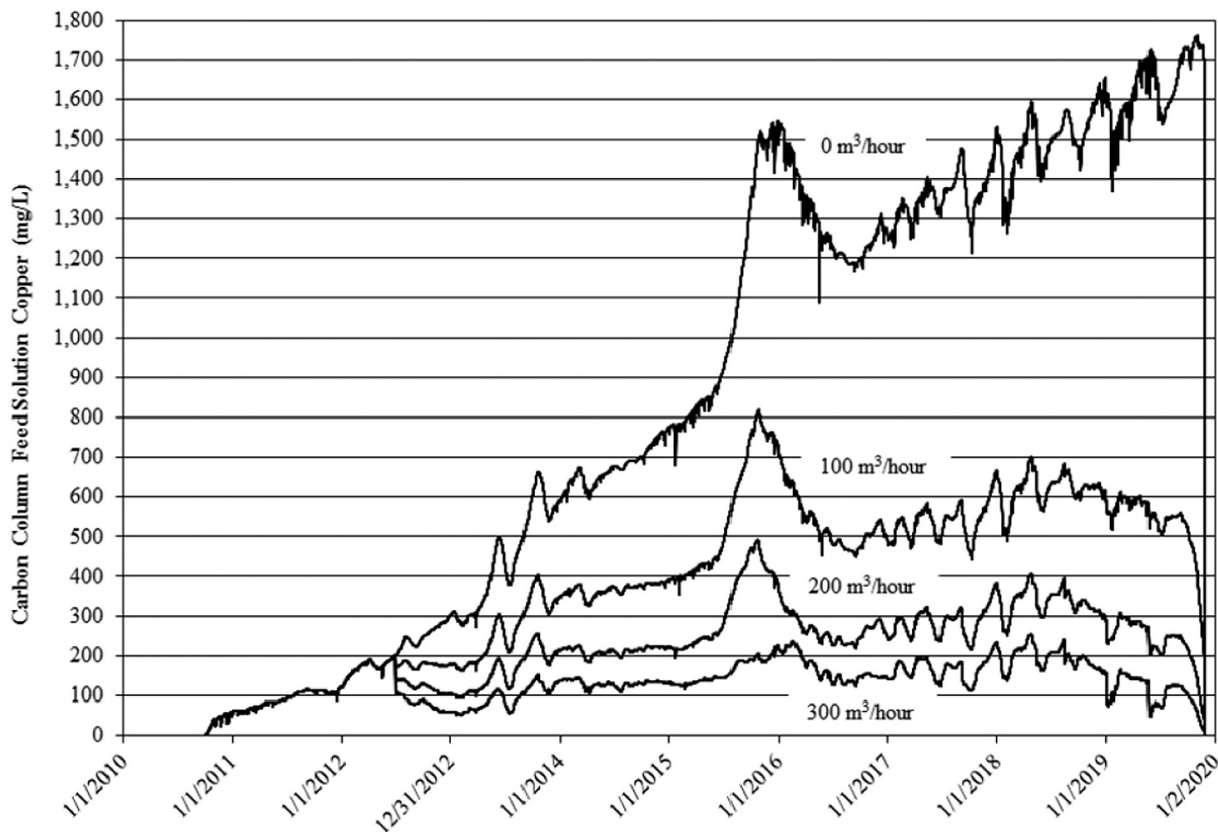


Fig. 8. Dynamic mass balance simulations results from Copler SART plant design (Botz et al., 2011b). (Authorized by Miner Metall Proc, SME).

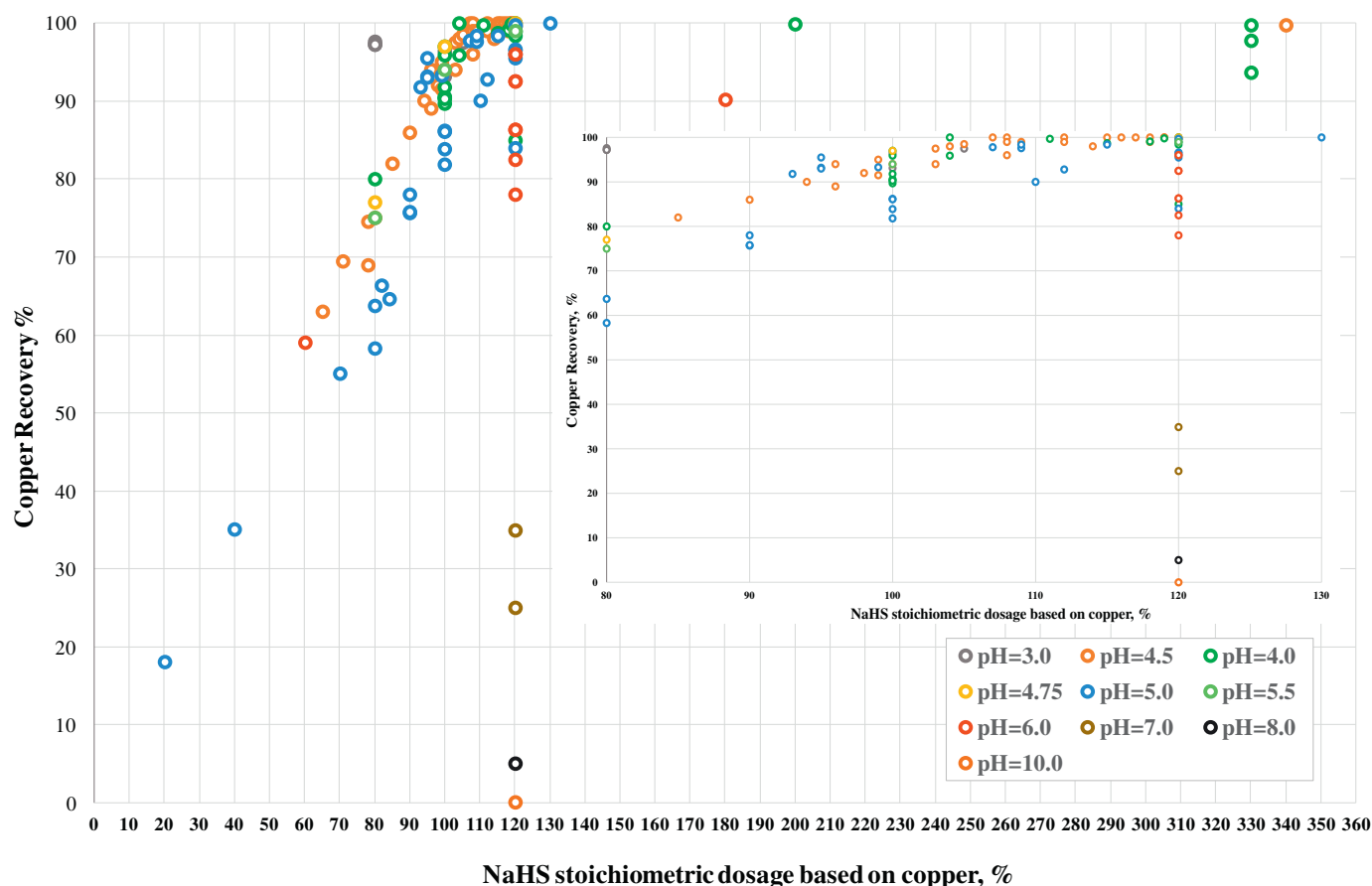


Fig. 9. Experimental results of the copper recovery respect to pH and sulfide stoichiometric dosage based on copper. These data have been collected from: MacPhail et al., 1998; Barter et al., 2001; Botz and Acar, 2007; Dreisinger et al., 2008; Ford et al., 2008; Botz et al., 2011b; Simons and Breuer, 2011; Lopez et al., 2014; Jimenez-Velasco et al., 2015; Simons et al., 2015; Simons, 2015; Fleming and Melashvili, 2016. The zoom graph illustrates the sulfide stoichiometric values between 80 and 120%.

Table 5
Operational data reported of the copper recovery respect to pH and sulfide stoichiometric dosage values.

SART plant	pH	S ⁻² stoichiometric dosage, %	Copper recovery, %	References
Telfer	4.5	116–138	90	Simons and Breuer, 2013
Yanacocha	4.0–4.5	120–140	80–99	Guzman and Acosta, 2009; Guzman et al., 2010; Botz et al., 2015
Gedabek	5.5	120	90–95	Estay et al., 2012a; Hedjazi and Monhemius, 2014
Mastra	4.0–5.0	115	90	Lawrence and Lopez, 2011; Kratochvil et al., 2013

SART plant (Guzman and Acosta, 2009; Guzman et al., 2010; Vargas et al., 2013; Botz et al., 2015), and the Gedabek SART plant (Estay et al., 2012a; Hedjazi and Monhemius, 2014), which contain a high silver content in the cyanide solution fed into the SART process (in both cases the silver content is higher than 5 mg/L), achieving silver recoveries close to 100% for sulfide stoichiometric dosages based on copper reported in Table 5.

Zinc has a similar behavior to the silver in the SART process, although the ZnS specie achieves recoveries over 90% when pH is below 7.0 (Littlejohn et al., 2013; Simons et al., 2015; Simons, 2015). Zinc also affects the copper recovery when sulfide stoichiometric dosage based on copper is < 100% (Simons et al., 2015). Hence, the sulfide stoichiometric dosage must be carefully defined when zinc is present in the cyanide solution, particularly for Merrill-Crowe plants, where it is recommended to define the sulfide stoichiometric dosage as a function of the copper and zinc.

The effect of gold on the copper recovery of the SART process is negligible, even in terms of sulfide consumption (Simons et al., 2015). However, there are works indicating gold precipitation for pH values below 4.0 (Guzman et al., 2010; Vargas et al., 2013; Simons et al., 2015;

Simons, 2015), even reaching precipitation values close to 100% at pH 2.0 (Simons, 2015). This last work demonstrates the effect of sulfide dosage in gold precipitation, increasing it at pH 4.0 when sulfide stoichiometric dosage is higher than 120%. Simons (2015) claims that gold sulfide species are generated at pH values below 3.5, especially when silver and zinc are present in the solution. Further studies must be developed in order to understand the favorable conditions to avoid gold precipitation, since the value of gold in the SART precipitate will be penalized according to the value in the dore metal.

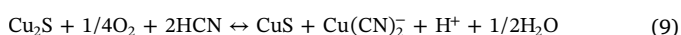
Other elements can precipitate in the SART process having a low impact in the copper recovery, such as molybdenum (Dreisinger et al., 2008), nickel (Simons et al., 2015; Simons, 2015) and iron (Dreisinger et al., 2008; Simons et al., 2015). These elements present precipitation values around 10%, although in the case of iron and nickel, they can increase this value at pH below 4.0 (Simons, 2015). Another element reported in literature is arsenic, which can reach precipitation values around 45% at pH value of 4.2, and sulfide stoichiometric dosage based on copper of 120% (Lopez et al., 2014).

To sum up, the presence of different elements in the cyanide solution fed into the SART process will increase the sulfide consumption,

and it could affect the copper recovery when sulfide content is limited (silver, zinc, arsenic). Also, the excess of sulfide and operation pH must be carefully controlled in order to avoid or minimize gold, iron and nickel precipitation. Hence, sulfide stoichiometric dosages based on copper values around 120%, and pH values between 4.0 and 5.0, are recommended for design and operation purposes, considering experimental work in order to support these values.

3.2.4. Effects of the residence time

Typical values of residence time used in the precipitation stage are around 10–15 min (MacPhail et al., 1998; Barter et al., 2001; Dreisinger et al., 2008; Ford et al., 2008; Guzman et al., 2010; Botz et al., 2011b; Lopez et al., 2014). This range of residence time is enough to ensure the copper recovery expected. However, specific works evaluating the effect of residence time have been performed at laboratory and plant scale (Simons and Breuer, 2013b; Simons, 2015), showing losses in the copper recovery when residence time has increased, explained by the oxidation of Cu_2S into CuS , according to Eq. (8), or by re-dissolution (see Eq. 9) to copper-cyanide complex.



Additionally, the CuS specie can re-dissolve into SCN^- for long residences times, explaining the characterization of the Yanacocha's precipitate (Simons, 2015), which contains high contents of CuS and copper thiocyanate (Guzman et al., 2010). These suggestions must be ratified with further studies focused on understanding the precipitate characterization under different sulfidization reaction conditions. In the same way, a Telfer diagnosis analysis (Simons and Breuer, 2013b) presented copper re-dissolution with no sulfide excess (Eq. (9)), and no copper re-dissolution when sulfide is added in excess in the cyanide solution.

Based on this evidence, Fleming and Melashvili (2016) suggested the use of sulfide dosage with no excess, minimizing the residence time in the precipitation reactor, and even evaluating its elimination in order to reduce the favorable conditions to form CuS . Accordingly, Stewart and Kappes (2012) proposed a SART process with no precipitation reactor and using only the pipeline as reaction stage, based on experimental results (not reported) which show reaction times of sulfidization of few seconds. These propositions could reduce the size of installations in a SART plant, although it must be demonstrated with further experimental results of copper recovery values at different residence times.

3.2.5. Effects of temperature

Some works have studied the effect of the temperature in the SART process (Ford et al., 2008; Littlejohn et al., 2013) showing a negligible effect on the copper and cyanide recovery under temperature values typical for cyanidation plants. However, temperature can promote the increasing of HCN gas generation in the SART process (Estay et al., 2012c). This fact must be considered in the equipment seal and scrubbing system design.

3.2.6. Control aspects, reagents dosage, agitation and recycling

The control of acid dosage is carried out by using a pH-controller in the whole experimental and operational experiences of the SART process. Instead, the sulfide dosage has been specified to operate using the results of copper concentration from sampling and by using oxidation reduction potential (ORP)-controller. The first way to control depends on the variability of copper concentration in the cyanide solution, i.e., for agitation plants this procedure can be uncertain. For this reason, the last experimental work and plants have included an ORP-controller obtaining adequate results (Dreisinger et al., 2008; Botz et al., 2011b; Lawrence and Lopez, 2011; Nodwell et al., 2012; Kratochvil et al., 2013; Lopez et al., 2014; Sanguinetti et al., 2014; Botz et al., 2015; Simons, 2015).

Another design aspect is the reagents dosage point, where the most

used option is the addition of acid and sulfide in the feed pipe, including an in line mixer for each reagent, in order to prevent localized pockets of reagents (Barter et al., 2001; Guzman et al., 2010; Simons and Breuer, 2013b; Pizarro and Estay, 2015).

On the other hand, the design of the agitator is a relevant aspect for the SART process, defining a slight agitation so it does not break the flocculated solids recycled from the thickener (Barter et al., 2001).

Finally, the work developed by Fleming and Melashvili (2016) proposed the elimination of recycling in the SART process, where there are no obvious benefits according to their experimental results, since the physical characteristics of solids after five cycles of recycling were not different. If recycling is not necessary, the SART process could reduce the capital and operational costs. However, this work does not show results of settling and filtration rates under any condition of recycling, thus further research at different scales must be performed in order to ensure the benefit of recycling elimination.

3.3. Thickening of the copper precipitate

While the precipitation stage is the core of the SART process, the thickening of the copper precipitate is the step where the performance of the whole process must be ratified. The aim of this unit operation is to clarify the overflow, minimizing the content of the solids precipitate going into neutralization stage, and increasing the solids percentage in the underflow, in order to improve the performance of the filtration step. Hence, the wrong design or operation of this stage could increase the capital cost and reduce the precipitate production. A good example of this fact were the operational issues of the Gedabek SART plant related to the thickener, since the high solid content in the overflow decreased the whole copper recovery of the SART process around 40 points, as a result of the copper re-dissolution in the neutralization stage. Several modifications in the process operation were implemented to solve these issues (Estay et al., 2012a). This experience demonstrates the value of a good design and operation of the thickening stage.

Although the settling rate parameter should be carefully selected to minimize the solids content in the overflow, the residence time in the thickener must be also considered to avoid the oxidation of sulfide phenomena (Simons and Breuer, 2013b).

Thereby, the main aspects of design and operation that must be considered are: i) the settling rate and residence time, ii) the solids content in the underflow, iii) the control criteria for recycling, and iv) the control of solids content in the overflow (turbidity).

The settling rate of solids (m/h) can be represented by the rise rate of solution ($\text{m}^3/\text{m}^2\text{h}$) used to design the thickener. These parameters depend on the flocculant dosage and the solid contents in the feed flow to the thickener. In this respect, there is few data published on the four SART plants, as shown in Table 6. The rise rate used in these plants is $< 4.0 \text{ m}^3/\text{m}^2\text{h}$, achieving solids content in the underflow over 10%, except for the Gedabek plant, because of the low recycling value. These values of rise rate were obtained using flocculant dosages ranging from 2.0 to 3.0 g/m^3 . In the case of the Telfer SART plant, the low rise rate used increases the residence time of the slurry, promoting the re-dissolution explained before. Hence, the rise rate for designing should be defined in a range between 2.0 and 4.0 $\text{m}^3/\text{m}^2\text{h}$, since it has been endorsed by settling test results avoiding the excess of residence time which can promote the sulfide oxidation in the thickener.

On the contrary, the solids content in the underflow should be the highest value, while the bed level does not increase the total suspended solids in the overflow in order to improve the performance of filtration stage. In this regard, the typical value reported is around 10–15% (Barter et al., 2001; Ritcey, 2005; Estay et al., 2010), which is supported by operational results shown in Table 5.

Another relevant aspect of design is the control criteria for recycling. In this case, some SART plants, such as Telfer and Yanacocha, operate in a full recycling mode until reaching a set value of solids content in the underflow, so a bleeding of underflow slurry is

Table 6
Data from thickening of the copper precipitate stage published for different SART plants.

SART plant	Diameter, m	Rise rate ^a , m ³ /m ² h	Flocculant dosage, g/m ³	Recycling percentage, %	Underflow solids content, %	References
Telfer	13.5	0.42	2.0	~100 (semi-continuous)	15	Barter et al., 2001, Simons and Breuer, 2013
Yanacocha	22	3.7	3.0	80	10–20	Guzman et al., 2010; Botz et al., 2015
Gedabek	8	2.8	2.0	3–10	0.5–1.0	Estay et al., 2012a; Hedjazi and Monhemius, 2014
Maricunga	20	2.4	–	95	15	Ford et al., 2008; Pizarro and Estay, 2015

^a These values have been estimated based on thickener diameter and feed flow data.

discharged into the filtration stage (Guzman et al., 2010; Vargas et al., 2013; Simons and Breuer, 2013b). Instead, another way to control the SART process recycling is setting the solids content in the feed slurry to thickener in order to ensure the settling rate of solids, just as the Gedabek SART plant experience has demonstrated (Estay et al., 2012a; Hedjazi and Monhemius, 2014), keeping the solids content in the feed flow below 1%, ensuring an optimum settling rate (Botz et al., 2011b; Estay et al., 2012a; Stewart and Kappes, 2012). In this respect, it is recommended to analyze the design of the recycling control considering its impact on the filtration stage, according to the solids content in the underflow, and the effect of total suspended solids (TSS) in the overflow. This parameter (TSS or turbidity) must be measured systematically in a SART plant to control the overall recovery of the process.

Finally, the solids content and recycling ratio in the underflow cannot be obtained from laboratory experiments, due to the small quantity of copper precipitate that can be produced. This hinders the production of a permanent solids bed while a continuous recycled flow is fed into the precipitation reactor, because of the low underflow obtained from the copper precipitate generated. Hence, a pilot scale is highly recommended for the thickening step.

3.4. Filtration and drying of copper precipitate stages

The filtration stage must be performed after a neutralization of precipitate slurry from the thickener, using NaOH in order to avoid the HCN gas generation and reduction of the grade by adding lime, which might generate gypsum. The filtration stage should be developed in a filter press, including a squeezing step at high pressure to minimize the final moisture content. Hence, the final moisture reported in literature ranges between 50 and 65% (Ford et al., 2008; Botz and Acar, 2007; Botz et al., 2011b; Hedjazi and Monhemius, 2014; Pizarro and Estay, 2015). In the same way, filtration rates between 5.0 and 26 kg/hm² have been reported, using filter plates having a thick < 30 mm (Botz et al., 2011b; Pizarro and Estay, 2015). The test-work at pilot scale of this stage is highly recommended in order to reach representative results having enough samples of precipitate slurry. Indeed, the filtration stage must include a washing step to eliminate dissolved gold in the final cake moisture.

As discussed for the thickening stage, the small quantity of copper precipitate obtained at the laboratory scale makes a representative filtration testwork unfeasible, because the slurry requirements by filter suppliers are generally higher than the quantity of solids generated in laboratory tests. Hence, the most representative design parameters at the filtration stage should be obtained in a pilot plant.

On the other hand, a drying stage has been included in some SART plants to reduce the final moisture content obtained in the filter press up to typical commercial values from copper concentrates (9–11%), such as Maricunga and Copler (Ford et al., 2008; Botz et al., 2011b). These plants have installed a screw dryer. The rest of SART plants does not include a dryer (Telfer, Yanacocha, Gedabek), due to commercial conditions which accept a high moisture in the product or flow-sheet favorable conditions, such as Telfer, where the thickened and neutralized slurry is directly pumped into the flotation plant (Simons and Breuer, 2013b). From the Lluvia de Oro and Mastra SART plants, there

are no data published regarding filtration and a possible drying stage.

3.5. Neutralization stage

The neutralization step is required to raise the pH (10–11) of cyanide solution treated by precipitation before returning into the cyanidation plant. This unit operation uses milk of lime to increase pH, since NaOH is more expensive. For this reason, gypsum is generated according to Eq. (4), and HCN reacts to free cyanide in the form of Ca(CN)₂ (see Eq. (3)).

The residence time reported for design ranges between 10 and 25 min (MacPhail et al., 1998; Hedjazi and Monhemius, 2014; Pizarro and Estay, 2015), although there is no enough data reported on this parameter. Furthermore, it has been proposed to eliminate this reactor due to “this reaction is rapid”, and also because it can be performed in a pipeline (Stewart and Kappes, 2012). The latter suggestion has not been supported by test results.

On the other hand, lime consumption depends on sulfate and carbonate contained in the cyanide solution from copper thickener overflow. In case of sulfate, this anion is added in the precipitation stage with the sulfuric acid and according to recirculation flows in the cyanidation plant. Hence, the sulfate anion will build up, so the lime addition can be estimated considering the excess of sulfate (added in precipitation stage) and carbonate generated in the cyanide solutions. Typical consumption values reported are 0.5–0.9 kg Ca(OH)₂/m³ (Ford et al., 2008; Botz et al., 2011b).

3.6. Thickening and filtration of gypsum

The gypsum generated in the neutralization reactor must be separated from the cyanide solution in a thickening stage. The settling rate of this precipitate is higher than copper precipitate, having test results with values from 5.0 to 10.0 m/h (equivalent to a rise rate of 3.0–6.0 m³/m²h) (Ford et al., 2008). This observation has been ratified by plant design (Barter et al., 2001; Estay et al., 2012a; Pizarro and Estay, 2015). This stage also includes recycling of part of the underflow into the neutralization reactor. Also, flocculant dosages have been reported with values ranging from 1.0 to 2.0 g/m³ (Barter et al., 2001; Estay et al., 2012a; Botz et al., 2015).

Typically, for heap leaching circuits, where tailing dam does not exist, the SART process must include a filtration stage of gypsum. It is recommended a filter press to reduce the final moisture below 50% (Pizarro and Estay, 2015). Instead, the SART plant of Gedabek uses a rotating vacuum filter reaching 80% of final moisture (Estay et al., 2012a; Hedjazi and Monhemius, 2014). Also, an intensive washing step must be carried out in order to reduce gold and free cyanide losses in the gypsum cake moisture.

3.7. Scrubbing stage

The scrubbing system ensures the safety of the SART process, capturing and treating the HCN and H₂S generated in each equipment of the plant. The latter are sealed and connected to a scrubber, typically as packed bed absorption tower, where a NaOH solution (10–20 wt%)

absorbs HCN and H₂S from the air, generating NaCN and Na₂S. These reactions are rapid, so the height of the tower is < 3 m. The correct design of this system must be based on a HCN and H₂S concentration in the air conducts, and sealed equipment below 4.7 ppm, in order to avoid risks for personnel in case of leaks. In this context, the airflow for vent system must be estimated according to the HCN and H₂S gas generation. A model to estimate the HCN gas generation in the SART process has been previously developed to identify the conditions promoting gas generation and define the correct airflow for the scrubbing system (Estay et al., 2012b).

On the other hand, a more compact technology could be used for the absorption equipment, replacing the conventional packed bed tower by a hollow fiber membrane contactor, such as are currently treated air flows containing CO₂ or NH₃ (Klaassen et al., 2005).

3.8. Copper concentration in the feed solution

Copper (or zinc) concentration is not constant for the life of a plant, and depends on the mine plan (grade and throughput) and mineralogy (cyanide-soluble copper content in the ore). Fig. 8 shows a simulation of copper concentration profile during the life of a heap leach plant (Botz et al., 2011b). Even though the limit established for copper concentration is achieved, the copper concentration fed into the SART plant is highly variable. This can decrease the NPV, when the design criteria selected for copper concentration is the peak in the life of the plant. Therefore, the process capacity and the performance of the SART plant are diminished when the design copper concentration is far from the highest values. Further, copper concentration profiles in an agitated leach plant are noisier than those in heap leach processes, as is the case of Yanacocha – where the mineralogy determines a start/stop operation according to the cyanide-soluble copper content in the ore (Guzman and Acosta, 2009; Guzman et al., 2010). On the other hand, the variability of copper concentration in the feed solution can modify the solids content in the precipitation reactor, affecting the settling rate of the solids precipitate in the thickener. Hence, it can expect an increase of solids content in the overflow, and therefore a decrease in the overall copper recovery, as mentioned in Section 3.3. Hence, the SART plant design – in particular, the capacity selected – must consider the copper concentration profile expected in the life of the plant. Further, the control philosophy of the underflow recycling should include the variability of copper concentration in the feed solution to keep the solids content fed into the thickener below 1%, ensuring the settling rate (Botz et al., 2011b; Estay et al., 2012a; Stewart and Kappes, 2012).

For the above reasons, the SART process could be designed considering operation stops when copper concentration in the feed solution goes below a threshold associate to a critical NPV. However, this operation mode must include instrumentation and a control philosophy according to frequent start-ups.

4. Current SART plants under operation

Seven SART plants have operated to date in the entire world, and several projects are under study (Estay et al., 2012c; Adams, 2013; Estay et al., 2014a; McGrath et al., 2015). Table 7 shows a summary of the SART plants currently operating in the world. A brief description for each SART plant is presented in what follows.

4.1. Telfer

The Telfer SART plant treats 40–60 m³/h of BLS from a carbon in leach (CIL) operation (Barter et al., 2001; Simons, 2015). This plant has not filtration of copper precipitate and gypsum stages, since the copper slurry produced in the thickener is neutralized and pumped into the flotation plant, and gypsum slurry is sent to the CCD circuit. A target copper concentration below 70 mg/L in the treated solution has been defined to set sulfide dosages (Simons, 2015).

4.2. Yanacocha

The Yanacocha SART plant treats a PLS nominal flow of 1200 m³/h (the design flow is 1400 m³/h), coming from a CCD circuit which treats the slurry leached in an agitation plant. This SART plant operates in an on-off mode, depending on the cyanide-soluble copper content in the ore (Guzman et al., 2010). The cyanide solution treated in the SART process is going into a carbon in column (CIC) plant to recover gold. Similarly to Telfer, the Yanacocha SART plant pumps the gypsum slurry into a CCD circuit, although it includes a copper precipitate filtration in press filter. Moreover, Yanacocha is the only SART plant including an AVR process to concentrate the free cyanide recovered in the SART process (Vargas et al., 2013). This SART plant produces a copper precipitate having 6–50% of copper grade. This value is lower than typical values observed in the SART process, due to the high content of silver and silica contamination in the PLS, which decreases the copper grade in the precipitate. Moreover, this value can be explained by the oxidation of Cu₂S in the thickener, producing CuS containing less relative copper grade (Guzman et al., 2010).

4.3. Lluvia de oro

The Lluvia de oro SART plant was installed to treat a barren solution (BLS) coming from a CIC plant. This plant was operated during six months until the cyanide-soluble copper in the ore decreased (Lawrence and Lopez, 2011).

4.4. Gedabek

The Gedabek SART plant treats a nominal PLS flow of 100–120 m³/h (design flow of 140 m³/h) coming from heap leaching plant and the treated cyanide solution is going into a resin in column plant to recover gold (Hedjazi and Monhemius, 2014). This plant does not include a drying stage, selling the copper precipitate with 55% of moisture. The copper grade in the precipitate is lower than typical values due to the silver present in PLS, which precipitates in the SART process.

4.5. Mastra

The Mastra SART plant treats a nominal BLS flow of 90–110 m³/h (design flow of 120 m³/h) coming from a CIC plant that treats the PLS of an agitation leaching with CIP operation. Thus, the treated solution from SART is recycled into the leaching plant (Lawrence and Lopez, 2011; Kratochvil et al., 2013).

4.6. Maricunga

The Maricunga SART plant treats a PLS flow of 750 m³/h from a heap leach plant. This plant includes all unit operations described in Fig. 3, producing a copper precipitate having a final moisture of 10% (Ford et al., 2008).

4.7. Copley

The Copley SART plant treats a PLS flow of 380 m³/h from a heap leach plant. Just as Maricunga SART plant, the Copley SART plant includes all unit operations described in Fig. 3 (Botz et al., 2011b).

5. Safety aspects

The SART process involves handling of slurries and cyanide solutions at low pH for different unit operations included in the process. Under these conditions, the cyanide content in the solution is present as HCN_(aq), which favors the potential emission of HCN to the environment. Furthermore, the presence of sulfide in the acid solutions favors the potential generation of H₂S. These conditions are addressed by the

Table 7

Data of SART plants under operation. Updated from Estay et al., 2012c, 2014a; Adams, 2013; McGrath et al., 2015.

SART plant	Telfer	Yanacocha	Lluvia de oro	Gedabek	Mastra	Maricunga	Copler
Company	Newcrest Mining Ltd	Newmont Mining Corp	NWM Mining	Anglo Asian Mining	Koza Gold Corp	Kinross Gold Corp	Alacer Gold Corp
Country	Australia	Peru	Mexico	Azerbaijan	Turkey	Chile	Turkey
Capacity, m ³ /h	60	1400	340	140	120	750	380
Flow treated	BLS	PLS	BLS	PLS	BLS	PLS	PLS
Leaching plant	Agitation Leach-CIL	Agitation Leach-CIC	Heap Leach	Heap Leach	Agitation Leach-CIP	Heap Leach	Heap Leach
[Cu] feed, mg/L	1000	1000	150	800	1500	450	400
Cu Recovery, %	90	80–99	90	90–95	90	90	94
Cu production, t/d	0.9	20	1.0	2.5	4.0	9.0	3.4
Copper grade in precipitate, %	70	6–50	65	55–60	55–65	70	68–74
Year startup	2006	2008	2008	2009	2010	2012	2013

SART plant design to ensure personnel safety by taking into consideration the following general criteria: i) the process equipment operating under acid conditions must be sealed and connected to a gas scrubbing system to neutralize potential HCN or H₂S emissions, ii) the process must consider neutralization to pH 11–12 of the slurry feeding the precipitate filtration stage, iii) redundant pH-controllers must be installed in critical equipment (e.g., precipitation reactor, copper precipitate thickener, slurry neutralization tank and neutralization reactor), iv) stationary HCN and H₂S sensors must be placed in the process building, critical equipment and scrubbing system, and v) the operators must use portable sensors set at 4.7 ppm (Estay et al., 2010). The stationary and portable sensors must be interlocked with the main automation controller of the plant to alarm a risk condition, and following the safety standard and procedures of each plant. Another safety aspect is the reagents dosage system, particularly sulfuric acid and sulfide along with containment systems (Estay et al., 2010; Nodwell et al., 2012).

On the other hand, a model that predicts HCN gas generation for the SART process has been developed which can be used to estimate the risk conditions for each unit operation (Estay et al., 2012b). The results of this model show an average HCN gas concentration going to the scrubbing system < 1.0 ppm for typical operational conditions in the SART process. Moreover, the precipitation reactor is the most critical equipment in the SART process, resulting in an HCN gas concentration around 10 ppm. These results depend on the cyanide/copper ratio in the feed solution of the SART process, and the drag-air flow/feed solution ratio for each equipment. Therefore, the HCN gas concentration must be regulated establishing a correct drag-air flow/feed solution ratio.

Another risk aspect of the SART process is the storage and drying stage of the copper precipitate. This precipitate contains sulfide minerals, which can be available to spontaneous combustion under favorable conditions of oxygen exposure and moisture content (Yang and Wu, 2013). This fact demands to include important safety criteria in the storage facilities, such as avoiding large quantities of precipitate stored for extended periods, minimizing air contact, avoiding natural dried and including the necessary installations to ensure a safety area, such as fire protection system and a proper handling of the bags (Estay et al., 2013b).

6. Economic impact

6.1. Capital costs

The capital costs for the SART process will depend on the local cost for labor, supplies and transport, including the environmental conditions and the mining company standards for facilities. A relevant factor to determine the capital cost is the unit operations in the SART process. Despite these factors, there are data published based on estimations and real values. Thus, the size and capital cost for the SART process will

depend on the treated flow (m³/h). The range of estimations values is wide: 60.8 kUS\$/m³/h (Barter et al., 2001), 30 kUS\$/m³/h (Bustos et al., 2008), 18–36 kUS\$/m³/h (Stewart and Kappes, 2012), 60 kUS\$/m³/h (Estay et al., 2012c), 35.7 kUS\$/m³/h (Sanguinetti et al., 2014), 60–90 kUS\$/m³/h (Estay et al., 2014a), 90 kUS\$/m³/h (Estay et al., 2014b) and 13–47 kUS\$/m³/h (Baker et al., 2017). These values are contrasted with real capital cost for the Maricunga SART plant: 106.7 kUS\$/m³/h (Danielson, 2013), and Yanacocha SART plant: 7.2 kUS\$/m³/h (Sevilla, 2017). The highest capital cost is reported by the Maricunga SART plant, due to the severe environmental conditions (4500 m.a.s.l.) that were forced to include heating and ventilation systems. Also, the instrumentation and control standard was higher than the typical mining process plants (Danielson, 2013). Furthermore, the Maricunga SART plant included the complete unit operations described in Fig. 3, while the Yanacocha SART plant did not include gypsum filter, copper precipitate drier and building. The low capital cost for Yanacocha can also be explained by the date when it was constructed, before the rise of labor and supplies costs for the mining sector.

6.2. Operational costs

The operational cost of a SART process is determined by reagents consumption (sulfuric acid, sulfide and lime). The sulfide reagent depends on copper content in the feed flow. In turn, acid and lime depend on the WAD cyanide and carbonate content in the feed flow. Thereby, the operational costs reported in literature are: 0.4 US\$/m³ (Adams et al., 2008), 1.1 US\$/m³ (Ford et al., 2008), 1.15 US\$/m³ (Bustos et al., 2008), 2.72 US\$/m³ (Estay et al., 2014b), and 6.0 US\$/m³ (Sanguinetti et al., 2014). The last value reported has been estimated for zinc treatment containing high zinc concentration (2500 mg/L). This fact demonstrates that operational costs for a SART plant will be defined by metal and cyanide concentration in the feed flow. In this respect, some operational cost estimations reported the NaHS as the dominant cost in the SART process, presenting values ranging between 28 and 70% of the total cost (Ford et al., 2008; Bustos et al., 2008; Estay et al., 2014b). Particularly, when the free cyanide content in the feed flow is high, the acid and lime consumption will increase with no benefits associated, due to the acid and lime consumed (see Eqs. (2) and (3), respectively). This fact could be critical for high capacities of the SART process, as will be explained in the next section.

In order to estimate the operational costs for the SART process, unitary prices for acid, NaHS and lime of 100 US\$/t acid, 1000–1500 US\$/t NaHS, and 130–200 US\$/t CaO have been used (Adams et al., 2008; Bustos et al., 2008), although these values will depend on the local prices for each project.

Regarding the reduction of the operational costs of the SART plant, specifically for NaHS, the use of on-site bio-generated H₂S has been proposed (Lawrence et al., 2007; Adams et al., 2008). However, the economic benefit must be determined for each case, and few detailed

estimations of the cost-saving have been reported for this technology.

6.3. Economic evaluation

The economic evaluation of the SART process is generally developed considering the process' own income, such as recovered copper (or another metal) and regenerated cyanide, omitting other benefits, such as the environmental impact (lower cyanide transportation, lower cyanide content in leach tails), and the improvements in the whole gold extraction process (reduction of cyanide consumption, ensured gold recoveries in carbon adsorption, ensured clean dore metal, lower total dissolved solids content in cyanide solution). In this context, a correct economic evaluation should consider a base-case of a gold cyanidation plant with no SART process compared with the same plant including a SART process. An analysis of this type has been performed demonstrating the benefits of SART process in a gold mine containing high cyanide-soluble copper content in the ore, making feasible the gold project (Estay et al., 2012c). This work shows that net present value (NPV) of a gold project increases between 50 and 200% when SART process is implemented, depending on the project life. When this analysis is assessed, it can be explained why the SART process has had an exponential interest in the gold industry.

Nevertheless, if a stand-alone economic evaluation is performed (only considering own income and consumption of the SART process), the profitability of this technology is positive, estimating simple payback between 1.5 and 2 years (Ford et al., 2008; Bustos et al., 2008; Sanguinetti et al., 2014).

In order to define the optimum NPV for the SART process, it is recommended to evaluate different capacities for the SART plant (Bustos et al., 2008; Estay et al., 2012c) considering an integrated mass balance in the cyanidation plant. In fact, in Section 4.1, it has been explained that the capacity of the SART plant will define the copper concentration in the feed flow, ensuring the reagents consumption and capital cost. Hence, the optimum NPV will be determined by an optimum SART plant capacity, which must also consider the set copper concentration as explained in Section 4.1. Fig. 10 shows an analysis performed to estimate the optimum capacity and NPV for a SART plant project where a peak of NPV is clearly obtained (Bustos et al., 2008). This maximum point in the curve is explained by the increase in fixed operational costs (energy consumption by pumping, maintenance and labor) and capital cost given by the feed flow (residence time in reactors, rise rate in thickeners). The incomes from copper production and cyanide recovered are relatively constant for a particular value of SART plant capacity and copper concentration in the solutions inventory. Indeed, Eq. (7) shows that – as the SART plant capacity increases – the copper bleeding produced by the SART process is larger than that from the leach tails. Hence, this last flow will be determined by copper concentration, which will tend asymptotically to a minimum value. Such

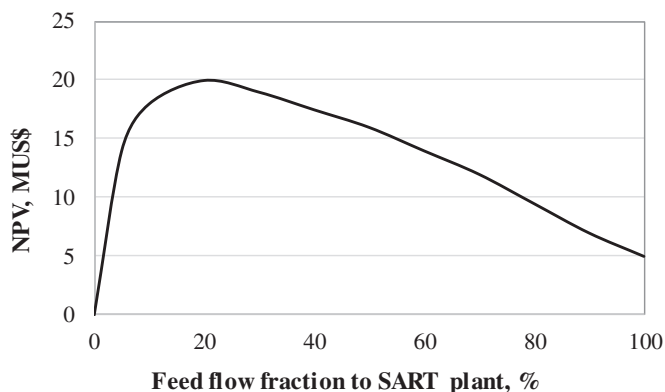


Fig. 10. SART plant and NPV optimum analysis for a case of heap leach cyanidation as shown in Fig. 4 (adapted from Bustos et al., 2008).

asymptotical behavior determines the constant copper and cyanide production for SART plants capacities over certain value (e.g. 20% of total PLS flow in the case of the Fig. 10). These aspects are valid for heap and agitation leaching processes, although the peak of the heap leaching NPV value will be established for lower capacities due to a lower final moisture content in leach tails than that in agitation leaching plants (Bustos et al., 2008).

The earlier analysis is based on a high cyanide-soluble copper content in the ore (around 400 g/t in both cases). When the cyanide-soluble copper grade is lower, the NPV value will decrease due to income reductions generated by copper precipitate production. Thus, there is a limit of cyanide-soluble copper content in the ore when fixed costs (labor, maintenance, energy consumption associated to solution pumping) are higher than incomes, decreasing NPV towards negative values. The aforementioned limit value will depend on local costs and the copper price, although including this methodology in a SART project will contribute to optimize capital and operational costs.

A number of additional aspects could affect the NPV value of a SART process and must be taken into account: the free cyanide concentration and the metals content in the feed flow. The free cyanide concentration determines the acid consumption in the precipitation reactor, as well as the lime consumption associated to the sulfate added with the acid. Thus, a high free cyanide concentration will increase the operational costs of the SART process with no profits associated. Hence, the inclusion of a SART process in a cyanidation plant does not necessarily increase the overall NPV of a gold mine. In the case of the metals content in the feed flow, its impacts on the overall NPV must be evaluated considering the detrimental effect of the particular metal in the cyanidation plant as base case (e.g., Hg, As, Zn), since the value of the SART precipitate will be penalized. In particular, it is recommended to treat the BLS rather than the PLS for high silver contents in the cyanide solution, because the value of the silver sulfide in the SART precipitate will be smaller than that of the dore metal.

7. Challenges and opportunities

The development of the SART process has been made by designers, engineers and operators having poor data from literature, particularly for the seven SART plants currently installed, which have generated data and publications on this technology. This situation demonstrates that further research must be performed in order to optimize and support this process. From the revision presented here, there are challenges and opportunities which should be studied henceforth.

7.1. Optimum sulfide dosage

According to the analyses shown in Section 4.2, there are doubts about the effect of excess of sulfide dosage, especially for high residence times. Apparently, CuS specie is formed consuming sulfide during the sulfidization reaction (Guzman et al., 2010; Estay et al., 2013b), or by oxidation after reaction (Simons and Breuer, 2013b; Simons, 2015). On the other hand, an adsorption of sulfide species on the copper precipitate has been proposed (Fleming and Melashvili, 2016). Further studies should be performed in order to determine the reason for sulfide consumption for improving the sulfide dosage control and reducing the sulfide consumption.

7.2. Reduction of the residence time in the precipitation reactor

As mentioned before in this review, there are authors proposing the reduction of residence times in the precipitation reactor, even eliminating it (Stewart and Kappes, 2012; Fleming and Melashvili, 2016). This proposition must be supported by experimental work. If the residence time can be reduced, the capital cost of the SART process can decrease.

In the same way, Fleming and Melashvili (2016) proposed the

elimination of recycling of precipitate slurry from thickener underflow into the precipitation reactor. As well as the reduction on residence time, this proposition must be confirmed by experimental work.

7.3. Optimum design of the copper precipitate thickener

The optimal separation of copper precipitate is critical to ensure the overall copper recovery in the SART process. An inadequate definition of the settling rate will trigger an increase in solids content in the overflow, losing copper precipitate production by re-dissolution at the neutralization stage. On the other hand, a conservative value of settling rate will increase the residence time in the thickener, promoting sulfide oxidation and re-dissolution of copper precipitate observed in the SART plants of Yanacocha and Telfer (Simons and Breuer, 2013b, Simons, 2015). Hence, future SART process testworks and design should include a critical analysis of the couple settling rate-residence time to define the optimal thickener size.

7.4. Selective precipitation of zinc and copper

The cyanidation plants that include a Merrill-Crowe (MC) process and present cyanide-soluble copper in the ore will have zinc and copper concentration in the cyanide solution. In this regard, a SART process can be implemented, although the precipitate generated will be a mixture of ZnS and Cu₂S losing saleable value as copper precipitate or zinc precipitate. Thereby, a SART process has been assessed, including two precipitation stages, one for copper and one for zinc (Littlejohn et al., 2013; Baker et al., 2017), using different pH values for each step. This two stages-SART process can be an interesting solution for MC circuits where copper content will contaminate the zinc precipitate, although further experimental work, focused on solid-liquid separation stages and economic evaluation, must be developed to determine the profitability of this option, because the sulfide stoichiometric consumption for zinc (Eq. (6)) is higher than copper, and the price of zinc is lower than copper.

7.5. SART/GFMA

As mentioned in Section 3.2, in some cases the cyanidation plants require an integrated SART/AVR process to generate a concentrated free cyanide solution. On the other hand, over the last years, a membrane separation technology has been developed to recover cyanide in gold mining (Estay et al., 2013a): a gas-filled membrane absorption process (GFMA), which can perform both stages of AVR process (absorption and stripping) in one compacted equipment, reducing the size of the plant and ensuring the safety of the process, since the HCN is enclosed in the fibers of the membrane. A technical and economic comparison between AVR and GFMA processes has been conducted with promising results for the latter (Dai and Breuer, 2013; Estay et al., 2014b).

7.6. Reverse osmosis (RO) as pre-concentration process

Reverse osmosis membranes (RO) have been used to purify water from cyanide solutions at the Yanacocha mine (Lombardi, 2009). This process could be applied up-stream from the SART process in order to concentrate the solution to be treated by the SART plant, strongly reducing the plant design capacity (10 times). Having a ten-fold increase in Cu (and cyanide) concentration in these membrane treated solutions, the feasibility of the SART unit operations with such high concentrations must be verified.

7.7. Cyanide leaching of Cu-Au-Ag ores

There are oxide copper minerals having contents of gold and silver that might be unable to recover gold and silver by using conventional

acid leaching. For these cases, some alternatives of cyanide leaching have been proposed using the SART process to recover copper from cyanide solution. One alternative is to use cyanide leaching after acid leaching (Dreisinger et al., 2008), and the second alternative is a cyanide leaching of the whole ore (Estay et al., 2013c). In both cases, a SART plant must be considered. This could be a feasible solution for these minerals prompted to be studied and evaluated.

8. Conclusion

The SART process is an excellent example of technology development, since the first industrial application was implemented eight years after the first paper published about the process. This urgency for the SART process application is explained by the great benefits of this technology in the gold mining, allowing a profitable treatment of cyanide-soluble copper ores. This urgency encouraged designers, engineers and operators of gold processing plants to implement the SART technology using the limited information published to establish experimental test-work, and design parameters and operational criteria. All these efforts allowed to install and operate seven SART plants to date, increasing the knowledge and interest regarding this technology. Hereafter, research about the SART process should be focused on understanding key aspects of precipitation chemistry and the process optimization, which will probably promote the third technological break of gold mining, after the cyanidation and carbon adsorption development.

Acknowledgements

The author wishes to acknowledge the valuable contribution of Leoncio Sevilla, Mike M. Botz, Andrew Simons, Fabian Rodriguez and Paul Breuer. Also, the author wishes to acknowledge the support given by Sergio Bustos and ex-co-workers from Arcadis Chile. The language revision given by Elizabeth Troncoso and Pablo Mendoza is highly appreciated. This work was funded by the National Commission for Scientific and Technological Research (CONICYT) (Fund No. FB0809 PIA CONICYT).

References

- Adams, M., 2013. Impact of recycling cyanide and its reaction products on upstream unit operations. *Miner. Eng.* 53, 241–255.
- Adams, M., Lloyd, V., 2008. Cyanide recovery by tailings washing and pond stripping. *Miner. Eng.* 21, 501–508.
- Adams, M., Lawrence, R., Bratty, M., 2008. Biogenic sulfide for cyanide recycle and copper recovery in gold-copper ore processing. *Miner. Eng.* 21, 509–517.
- Alonso-Gonzalez, O., Nava-Alonso, F., Uribe-Salas, A., 2009. Copper removal from cyanide solutions by acidification. *Miner. Eng.* 22, 324–329.
- Baker, B., Rodriguez, F., Littlejohn, P., 2017. SART implementation at Gold Mines in Latin America. In: *World Gold 2017. CIM/ICM, Vancouver, Canada August 27–30*.
- Barter, J., Lane, G., Mitchell, D., Kelson, R., Dunne, R., Trang, C., Dreisinger, D., 2001. Cyanide management by SART. In: Young, C. (Ed.), *Cyanide: Social, Industrial and Economical Aspects*. TMS (The Minerals, Metals & Materials Society), pp. 549–562.
- Becker, J., Figueroa, A., Silva, P., Arriagada, F., 2012. Dynamic mass balance simulations in multi-lift leaching heaps. In: *HydroProcess 2012, 4th International Seminar on Process Hydrometallurgy, Santiago, Chile*.
- Botz, M., Acar, S., 2007. Copper Precipitation and Cyanide Recovery Pilot Testing for the Newmont Yanacocha Project. In: *Society for Mining, Metallurgy & Exploration (SME) Annual Meeting, Denver, February, 25–28*.
- Botz, M., Scola, J., Fueyo, R., de Moura, W., 2004. Cyanide recovery practice at Cerro Vanguardia. In: *SME Annual Meeting 2004 Preprints. The Society for Mining, Metallurgy and Exploration Inc., Littleton, Colorado*, pp. 641–644.
- Botz, M., Mudder, T., Akcil, A., 2005. Cyanide treatment: physical, chemical and biological processes. In: Adams, M.D. (Ed.), *Developments in Minerals Processing*. vol. 15. Elsevier B.V., Amsterdam, pp. 672–702.
- Botz, M., Fleming, C., Ford, K., 2011a. Cyanide leaching of gold-copper porphyries: chemistry and challenges. In: Deschênes, G., Dimitrakopoulos, R., Bouchard, J. (Eds.), *World Gold 2011. CIMM, Canada*, pp. 285–301.
- Botz, M., Kaczmarek, A., Orser, S., 2011b. Managing copper in leach solution at the Copler gold mine: laboratory testing and process design. *Miner. Metall. Process.* 28, 133–138.
- Botz, M., Guzman, G., Sevilla, L., 2015. Campaign testing the yanacocha sart plant with high-copper feed solution. *Society for Mining, Metallurgy Exploration (SME) Annual*

- Meeting, Denver, February, 15–18.
- Breuer, P., Dai, X., Jeffrey, M., 2005. Leaching of gold and copper minerals in cyanide deficient copper solutions. *Hydrometallurgy* 78, 156–165.
- Breuer, P., Sutcliffe, C., Meakin, R., 2011. Cyanide measurement by silver nitrate titration: comparison of rhodanine and potentiometric end-points. *Hydrometallurgy* 106, 135–140.
- Bustos, S., Estay, H., Arriagada, F., 2008. El Proceso SART: Una Oportunidad para Yacimientos de Oro-Cobre. In: VII Simposio Internacional de Mineralurgia, TECSUP 2008, Lima, Septiembre 13–15.
- Coderre, F., Dixon, D., 1999. Modeling the cyanide heap leaching of cupriferous gold ores part I: introduction and interpretation of laboratory column leaching data. *Hydrometallurgy* 52, 151–175.
- Dai, X., Breuer, P., 2009. Cyanide and copper cyanide recovery by activated carbon. *Miner. Eng.* 22, 469–476.
- Dai, X., Breuer, P., 2013. Comparison of AVR and gas membrane technology in cyanide recovery. In: ALTA 2013 Gold Conference, Perth, Australia.
- Dai, X., Jeffrey, M., Breuer, P., 2005. The development of a flow injection analysis method for the quantification of free cyanide and copper cyanide complexes in gold leaching solutions. *Hydrometallurgy* 76, 87–96.
- Dai, X., Simons, A., Breuer, P., 2012. A review of copper cyanide recovery technologies for the cyanidation of copper containing gold ores. *Miner. Eng.* 25, 1–13.
- Danielson, V., 2013. Slow start for SART: Promising technology could save industry millions in time. In: CIM Magazine, October 2013. Canadian Institute of Mining, Metallurgy and Petroleum.
- Demopoulos, G., Cheng, T., 2004. A case study of CIP tails slurry treatment: comparison of cyanide recovery to cyanide destruction. *Eur. J. Miner. Process. Environ. Prot.* 4, 1–9.
- Deschênes, G., Prud'homme, P., 1997. Cyanidation of a copper-gold ore. *Int. J. Miner. Process.* 50, 127–141.
- Dreisinger, D., Vaughan, J., Lu, J., Wassink, B., West-Sells, P., 2008. Treatment of the Carmacks copper-gold ore by acid leaching and cyanide leaching with SART recovery of copper and cyanide from barren cyanide solution. *Hydrometallurgy* 2008, 6th International Symposium, Phoenix, USA, 17–20 August 2008. Young, C.A. (Ed.). Society for Mining, Metallurgy and Exploration, Littleton, CO. pp. 740–749.
- Dzombak, D., Ghosh, R., Wong-Ching, G., 2006. Cyanide in Water and Soil: Chemistry, Risk and Management. CRC Taylor and Francis Group, Boca Raton, FL.
- Estay, H., 2013. Estimating the hydrogen cyanide generation: thermodynamic and mass transfer. In: Soto-Blanco, B. (Ed.), Cyanide: Occurrence, Characteristics and Applications. 2013. Nova Publishers, New York, USA, pp. 47–86.
- Estay, H., Arriagada, F., Bustos, S., 2010. Design, development and challenges of the SART process. In: Proceedings-HydroProcess 2010 – 3th International Workshop on Process Hydrometallurgy, Santiago, Chile.
- Estay, H., Carvajal, P., Hedjazi, F., Van Zeller, T., 2012a. The SART process experience in the Gedabek plant. In: HydroProcess 2012b, 4th International Workshop on Process Hydrometallurgy, Santiago, Chile.
- Estay, H., Carvajal, P., Arriagada, F., 2012b. The SART Process: An attractive technology to recover copper and cyanide from gold mining. In: M2R2 Workshop, Expomin 2012, (April 2012a, Santiago), Chile.
- Estay, H., Becker, J., Carvajal, P., Arriagada, F., 2012c. Predicting HCN gas generation in the SART process. *Hydrometallurgy* 113–114, 131–142.
- Estay, H., Carvajal, P., González, K., Vásquez, V., 2013a. A theoretical study of SART precipitate generation: Operational and safety impacts. In: HydroProcess 2013a, 5th International Workshop on Process Hydrometallurgy, Santiago, Chile.
- Estay, H., Carvajal, P., González, K., Yañez, H., Bustos, W., Castro, S., Arriagada, F., 2013b. Cyanide leaching of copper-gold-silver ores. In: HydroProcess 2013b, 5th International Workshop on Process Hydrometallurgy, Santiago, Chile.
- Estay, H., Ortiz, M., Romero, J., 2013c. A novel process based on gas filled membrane absorption to recover cyanide in gold mining. *Hydrometallurgy* 134–135, 166–176.
- Estay, H., Orellana, C., Arriagada, F., 2014a. Future trends in the SART process. In: HydroProcess 2014, 6th International Workshop on Process Hydrometallurgy, Viña del Mar, Chile.
- Estay, H., Troncoso, E., Romero, J., 2014b. Design and cost estimation of a gas-filled membrane absorption (GFMA) process as alternative for cyanide recovery in gold mining. *J. Membr. Sci.* 466, 253–264.
- Fleming, C.A., 2005. Cyanide recovery. In: Adams, M.D. (Ed.), *Developments in Minerals Processing*. vol. 15. Elsevier B.V., Amsterdam, pp. 703–727.
- Fleming, C.A., 2016. Cyanide recovery. In: Adams, M.D. (Ed.), *Gold Ore Processing*, 2nd Ed. Elsevier, Amsterdam, pp. 647–662 Chapter 36.
- Fleming, C.A., Melashvili, M., 2016. The SART process: killing the sacred cows. In: XXVIII International Mineral Processing Congress (IMPC 2016), Quebec, Canada, 11–15 September.
- Fleming, C.A., Trang, C.V., 1998. Review of options for cyanide recovery at gold and silver mines. In: Randol Gold and Silver Forum '98. Randol International, Denver, Colorado, pp. 313–318.
- Ford, K., Fleming, C., Henderson, R., 2008. Application of the SART process to heap leaching of gold-copper ores at Maricunga, Chile. In: 40th Annual Meeting of the Canadian Mineral Processors, Ottawa, January 22–24.
- Guzman, G., Acosta, E., 2009. Proceso SART y su influencia en el proceso CIC Minera Yanacocha S.R.L. In: 29 Convención Minera, Perumin 2009, Arequipa, Perú, Septiembre 14–18.
- Guzman, G., Mamani, V., Arevalo, H., Vicuña, S., Vargas, L., Burger, B., 2010. SART/AVR circuit design and operation at Yanacocha gold mill. In: Precious Metals'10. Minerals Engineering International, Falmouth, pp. 27.
- Hedjazi, F., Monhemius, A.J., 2014. Copper-gold ore processing with ion exchange and SART technology. *Miner. Eng.* 64, 120–125.
- Izzat, R., Christensen, J., Pack, R., Bench, R., 1962. Thermodynamics of metal-cyanide coordination. I. pK, ΔH^0 , ΔS^0 values as a function of temperature for hydrocyanic acid dissociation in aqueous solution. *Inorg. Chem.* 1, 828–831.
- Izzat, R., Dee Johnson, H., Watt, G., Christensen, J., 1967. Thermodynamics of metal-cyanide coordination. VI. Copper(I)-and silver(I)-cyanide systems. *Inorg. Chem.* 6, 132–135.
- Jimenez-Velasco, C., Nava-Alonso, F., Uribe-Salas, A., Alonso-Gonzalez, O., 2015. Thermodynamic and experimental analysis of copper sulfide precipitation in copper-cyanide solutions. *Miner. Metall. Process.* 32, 22–29.
- Karimi, P., Abdollahi, H., Amini, A., Noaparast, M., Shafaei, S., Habashi, F., 2010. Cyanidation of gold ores containing copper, silver, lead, arsenic and antimony. *Int. J. Miner. Process.* 95, 68–77.
- Klaassen, R., Feron, P.H.M., Jansen, A.E., 2005. Membrane contactors in industrial applications. *Chem. Eng. Res. Des.* 83 (A3), 234–246.
- Kratochvil, D., Chan, N., Hall, A., 2013. Integrating SART into metallurgical flowsheets for cyanide recovery. In: ALTA 2013 Gold Conference, Perth, Australia.
- Kuyucak, N., Akcil, A., 2013. Cyanide and removal options from effluents in gold mining and metallurgical processes. *Miner. Eng.* 50–51, 13–29.
- Kyle, J.H., Hefter, G., 2015. A critical review of the thermodynamics of hydrogen cyanide and copper(I)-cyanide complexes in aqueous solution. *Hydrometallurgy* 154, 78–87.
- Lawrence, R., Lopez, O., 2011. Improving the economics of gold-copper ore projects using SART technology. In: Deschênes, G., Dimitrakopoulos, R., Bouchard, J. (Eds.), *World Gold 2011*. CIMM, Canada.
- Lawrence, R., Philippe, R., Fleming, C., 2007. Sulphide and ion exchange technologies for metal recovery and water treatment in the copper mining industry. In: *Proceedings-HydroCopper 2007 – 4th International Workshop on Copper Hydrometallurgy*. May 16–18. Viña del Mar, Chile.
- Lewis, A.E., 2010. Review of metal sulfide precipitation. *Hydrometallurgy* 104, 222–234.
- Littlejohn, P., Kratochvil, D., Hall, A., 2013. Sulfidation-acidification-recycling-thickening (SART) for complex gold ores. In: *World Gold 2013*, Brisbane. Australasian Institute of Mining and Metallurgy, pp. 149–155.
- Logsdon, M., Hagelstein, K., Mudder, T., 1999. The Management of Cyanide in Gold Extraction. International Council on Metals and the Environment, Ottawa, Ontario, Canada.
- Lombardi, J., 2009. The cyanide method of copper and copper-gold production. In: *Proceedings HydroCopper 2009*, 5th International Copper Hydrometallurgy Workshop, Antofagasta, Chile, pp. 94–101.
- Lopez, O., Petrovic, N., Krashenina, S., 2014. Copper and cyanide recovery from barren leach solution at the gold processing plant. In: XXVII International Mineral Processing Congress (IMPC 2014), Santiago, Chile, October.
- Lu, J., Dreisinger, D., Cooper, W., 2002. Thermodynamics of the aqueous copper-cyanide system. *Hydrometallurgy* 66, 23–36.
- MacPhail, P.K., Fleming, C., Sarbutt, K., 1998. Cyanide Recovery by the SART Process for the Lobo-Marté Project, Chile. *Randol Gold and Silver Forum*, Denver (April 26–29).
- Marsden, J.O., House, C.I., 2006. The Chemistry of Gold Extraction, Second ed. Society for Mining, Metallurgy and Exploration SME, Colorado, USA.
- McGrath, T., Simons, A., Dunne, R., Staunton, W.P., 2015. Cyanide recovery using SART – current status. In: *World Gold 2015*, Misty Hills, Gauteng, South Africa, 29 September–1 October 2015. Southern African Institute of Mining and Metallurgy, Johannesburg.
- Melashvili, M., Fleming, C.A., Dymov, I., Smolik, J., Lindsay, D., 2015. Cyanide recovery and detoxification study on Seabridge Gold's KSM project. In: 47th Annual Canadian Mineral Processors Conference, CMP 2015, Ottawa, Canada, January 20–22.
- Mudder, T.I., Botz, M.M., 2004. Cyanide and society: a critical review. *Eur. J. Miner. Process. Environ. Prot.* 4, 62–74.
- Nguyen, H., Tran, T., Wong, P., 1997. Copper interaction during the dissolution of gold. *Miner. Eng.* 10, 491–505.
- Nodwell, M., Kratochvil, D., Lopez, O., 2012. Risk management and mitigation for the SART copper cyanide recovery process. In: *HydroProcess 2012*, 4th International Workshop on Process Hydrometallurgy, Santiago, Chile.
- Pizarro, C., Estay, H., 2015. SART project: a new challenge for Maricunga. In: *CIM Los Andes Conference*, May 18, Santiago, Chile.
- Potter, G.M., Bergmann, A., Haidlen, U., 1986. Process of recovering copper and of option-ally recovering silver and gold by leaching of oxide and sulfide-containing materials with water-soluble cyanides. In: *U.S. Pat.* 4,587, 110.
- Ritcey, G., 2005. Tailings management in gold plants. *Hydrometallurgy* 78, 3–20.
- Sanguinetti, D., Mohammadi, F., Lopez, O., 2014. SART to remove zinc and copper from a silver Merrill Crowe barren leach solution. In: *HydroProcess 2014*, 6th International Workshop on Process Hydrometallurgy. Viña del Mar, Chile.
- Sceresini, B., 2005. Gold-copper ores. In: Adams, M.D. (Ed.), *Developments in Minerals Processing*. vol. 15. Elsevier B.V., Amsterdam, pp. 789–824.
- Sceresini, B., Breuer, P., 2016. Gold-copper ores. In: Adams, M.D. (Ed.), *Gold Ore Processing*, 2nd Ed. Elsevier, Amsterdam, pp. 771–801 Chapter 43.
- Sevilla, L., 2017. Personal Communication Regarding Yanacocha SART Plant. (June 2017).
- Shantz, R., Reich, J., 1978. A review of copper-cyanide metallurgy. *Hydrometallurgy* 3, 99–109.
- Simons, A., 2015. A Fundamental Study of Copper and Cyanide Recovery from Gold Tailings by Sulfidation. WA School of Mines. Curtin University, Perth, WA.
- Simons, A., Breuer, P., 2011. The effect of process variables on cyanide and copper recovery using SART. *ALTA 2011 Gold Proceedings*. Taylor, A. (Ed.). ALTA Metallurgical Services, Perth, Australia. pp. 175–187.
- Simons, A., Breuer, P., 2013a. Fundamental investigations of SART for cyanide and copper recovery. *CIM J.* 4 (3), 145–152 Canadian Institute of Mining, Metallurgy and Petroleum.
- Simons, A., Breuer, P., 2013b. The impact of residence time on copper recovery in Telfer Gold Mine's cyanide recycling process. In: *World Gold 2013*, Brisbane, Queensland,

- Australia. Australasian Institute of Mining and Metallurgy, Melbourne, pp. 189–196 26–29 September 2013.
- Simons, A., Breuer, P., Browner, R., 2015. The impact of metal cyanide species on the recovery of cyanide and copper using SART. In: World Gold 2015, Misty Hills, Gauteng, South Africa, 29 September–1 October 2015. Southern African Institute of Mining and Metallurgy, Johannesburg.
- Smith, A., Mudder, T., 1991. The Chemistry and Treatment of Cyanidation Wastes. Mining Journal Books Limited, London.
- Stewart, M., Kappes, D., 2012. SART for copper control in cyanide heap leaching. *J. S. Afr. Min. Metall.* 112, 1037–1043.
- Vargas, L., Guzman, G., Roux, E., Sevilla, L., 2013. Yanacocha Gold Mill and SART/AVR process 2013–2017. In: 1st Arcadis Gold Workshop, Santiago, Chile.
- Xie, F., Dreisinger, D., Doyle, F., 2013. A review on recovery of copper and cyanide from waste cyanide solutions. *Miner. Process Extr. M.* 34, 387–411.
- Yang, F., Wu, C., 2013. Mechanism of mechanical activation for spontaneous combustion of sulfide minerals. *Trans. Nonferrous Metals Soc. China* 23, 276–282.
- Zhang, Y., Fang, Z., Muhammed, M., 1997. On the solution chemistry of cyanidation of gold and silver bearing sulfide ores. A critical evaluation of thermodynamics calculations. *Hydrometallurgy* 46, 251–269.