Influence of water resources and metal ions on galena flotation of Rosh Pinah ore

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Synopsis

During galena flotation of Rosh Pinah milled material, metal ions and salts contents of various water resources (deionized, simulated circulated, lead concentrate thickener, lead tailing thickener and borehole) influenced mineral recoveries, upgrade ratios, selectivities, froth stability and flotation kinetics.

The various water resources employed during galena flotation caused activation, depression or selectivity effects on minerals due to the presence of different ions in solution. Metal ions in these water resources were adsorbed by the ore, whilst ions associated with gangue minerals (dolomite and quartz) were released into the flotation pulp. Lead concentrate thickener water caused depression of sphalerite and pyrite, increased fast floating fractions for silver, copper minerals, sphalerite and quartz (unwanted), and improved slow floating rate selectivity against pyrite and sphalerite. Lead tailing thickener water enhanced sphalerite recovery during galena flotation (unwanted), and increased fast floating fractions of pyrite. Western borehole water did not affect galena recovery, but sphalerite and pyrite recoveries were unacceptably too high.

Ions from copper, lead, and zinc salts tended to release high amounts of ions, such as calcium, magnesium, silicon, and manganese from gangue minerals (dolomite and quartz) during milling. During galena flotation, lead ions depressed sphalerite, pyrite and dolomite at a lead concentration of 400 ppm, but sphalerite was activated at a concentration of 800 ppm. Sphalerite was activated with copper ions (89% recovery, 2.09 upgrade ratio) and depressed with zinc ions (maximum recovery of 25%). This corresponds with findings in previous investigations. Dolomite and quartz were slightly activated with zinc ions. No evidence was found that lead and copper ions activated any gangue minerals during galena flotation.

Keywords: galena, water resources, metal ions, activation, depression, selectivity.

Introduction

Various cases are known where water quality and ions play a significant role during selective flotation of sulphide minerals, for example (i) water quality in general (Levay, et al., 2001), (ii) water quality at Mufulira (Ng'andu, 2001), (iii) activation, deactivation and depression by metal ions (Allison, 1982; Bessiere, et al., 1990; Finkelstein, 1997; Fuerstenau, 1999). These authors also discussed the various mechanisms involved during these processes on sulphide minerals.

Various sulphide and gangue minerals of concern for this investigation can be activated for flotation with metal salts under certain conditions, for example:

➤ galena with salts of manganese, lead, zinc, copper, nickel, iron, and silver (Rykl, 1964)
➤ sphalerite with salts of copper (Finkelstein and Allison, 1962; Prestidge, et al., 1994; Gerson, et al., 1999), silver (Sato, 1954), and lead (Winkler, 1935; Allison, 1982; Trahar, et al., 1997; El-Shall, et al., 2000)
➤ pyrite with salts of copper (Bushell and Krauss, 1962)
➤ quartz with salts of iron (pH 3–8), copper (pH 6-9) and magnesium (pH 10–12) (Kraeber and Boppel, 1934); barium in alkaline medium (Gaudin and Rizo-Patron, 1934); lead (pH 6.5–12), aluminium, zinc (pH 8.5), manganese (pH 8.5–9.4), and calcium. Activation was found to occur at the optimal pH for the hydroxy complex formation that is very nearly the pH at which the metal hydroxide precipitates (Fuerstenau and Palmer, 1976; Fuerstenau, 1999).

Depression of the following minerals of concern can be accomplished through the following means:

➤ *for sphalerite*—colloid precipitates of zinc salts (Fuerstenau, 1999), depression of copper-activated sphalerite due to magnesium occurs above pH 9 where the hydroxide starts to precipitate (Lascelles and Finch, 2001), cyanide can be used to eliminate copper sulphide from the sphalerite surface (Bessiere, et al., 1990)

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➤ *for pyrite*—cyanide is commonly employed to depress pyrite (Fuerstenau, 1982).

At Rosh Pinah (southern Namibia), valuable minerals, such as galena, silver and copper, must be selectively removed from the main valuable mineral sphalerite and water quality could influence this selectivity. A typical composition of the ore is shown in Table I.

During flotation of sulphides at Rosh Pinah plant, various factors can influence the performance of the flotation plant. Some factors are, amongst others, (i) precipitation and dissolution of ions, (ii) quality of water resources at the plant and, (iii) activation and depression induced due to above processes during milling and flotation.

At the Rosh Pinah plant, lead circuit water circulates from the lead tailings and lead concentrate thickeners back to the milling step. During this circulation, there is a buildup of ions due to dissolution from the milled material. The aim of the first part of the investigation was to simulate the buildup of these ions in the laboratory and determining the effect of these ions on flotation kinetics as well as activation or depression of minerals.

The second aim was to determine the effect of water quality from various sources at Rosh Pinah, such as tailing and concentrate thickeners from the lead flotation and borehole water. These different water resources contain different salt and ion contents. These salts could influence the froth stability and selectivity during sulphide flotation.

The aim of the third part of the investigation was to determine whether lead, copper and zinc ions absorbed by Rosh Pinah ore lead to activation or depression of the different minerals. No attempt was made to elucidate the mechanisms involved during activation or depression.

This work was merely to demonstrate the complexities involved on a typical base metal flotation plant, especially at Rosh Pinah.

Experimental procedure

Milling

Rosh Pinah material was milled at 60% solids for 5 minutes in a laboratory rod mill. Water added to the mill had a specific content to determine the influence of different water resources and ions in the water on flotation of milled material.

Reagents

SNPX (sodium normal propyl xanthate) from Senmin was

used as a collector at a dosage level of 50 g/t. SNPX is currently used at Rosh Pinah mine. It was added directly after the pulp from the mill was transferred to a standard Denver laboratory flotation cell. The conditioning time of the collector was 2 minutes before a frother was added and flotation started. Two frothers were used and are depicted as Frother A and Frother B.

Flotation procedure

During each flotation test, before the collector was added, deionized water was added to fill the 2 litre cell to a predetermined level before flotation commenced.

Two standard tests were performed with only deionized water added to the mill and flotation cell. During bulk flotation tests, one concentrate was accumulated over ten minutes of flotation. The two tests conducted were at similar conditions except for Frothers A and B used during the two tests, respectively.

During kinetic tests, 7 concentrate samples were taken after 20 and 40 seconds, 1, 1.5, 2, 4, 6 and 10 minutes, respectively. These tests were performed in a flotation cell fitted with an automatic scraper. In the first test, deionized water was added to the mill. After milling, pulp water was filtered off with a pressure filter. The solid material was then transferred to a flotation cell and flotation was performed. This was used as the standard kinetic test.

Circulated water was prepared according to the following procedure. After the ore was milled, water was filtered from the pulp and added to a next milling step where fresh run-of-mine Rosh Pinah material was used. This process was repeated 4 times and, after the 5th milling step, the pulp was transferred (without filtering off the water) to the cell for flotation. A water sample was taken from each filtered water product to determine the release of ions from the ore into the water.

During the third part of the investigation, the effect on flotation of overflow water of the thickeners of the tailing and concentrate of the lead flotation step at Rosh Pinah was investigated. At the Rosh Pinah plant, this water circulates back to the ball mill and the lead flotation cleaner column cells. Borehole water of the Eastern and Western ore field at Rosh Pinah mine was also evaluated in two separate tests. This water was evaluated as a possible source for the flotation plant. All tests were performed with Frother A and the test with Western ore field water was repeated with Frother B.

Different water resources were only added in the mill in order to determine the absorption or dissolution of ions during milling. At Rosh Pinah, the collector is added in the mill. Therefore, most important activation and depression effects occur in the mill itself.

In the fourth part of the investigation, copper, lead and zinc ions were dissolved in deionized water at different concentrations and added in the laboratory mill to determine their effect on activation and depression of minerals induced during milling of the ore. Reagents utilized were $CuSO_4.5H_2O$, $Pb(NO_3)_2$ and $ZnSO_4.7H_2O$. The copper and lead concentrations used were 400 and 800 ppm, respectively. The zinc concentration added was 58, 116, 230 and 916 ppm, respectively. These copper and zinc concentrations were used to simulate the high equilibrium levels of copper

Table I	
Typical mineralogical composition of Rosh Pinah ore	
Mineral	**Distribution (%)**
Sphalerite	9.2
Galena	1.8
Silver	25 ppm
Cu minerals (chalcopyrite/bornite/tennantite)	0.3
Pyrite	7.0
Dolomite	33.4
Quartz	40.1
Other (Barites, clay, etc.)	8.2

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(17 ppm) and zinc (0.34–10 ppm) that are present in the plant water after absorption by the ore. All the tests were performed with Frother A and the tests with 800 ppm copper and lead was repeated with Frother B. Only bulk flotation tests were performed as described above.

The temperature of the pulp during the flotation tests was 22±3°C. Cyanide circulates back in the plant at Rosh Pinah and could have an effect on flotation, but was not *per se* included during this investigation. No pH adjustments were made during the tests, but all were performed at about pH 8–9, that is the natural pH of the ore. During lead rougher flotation tests, the water level was kept at a predetermined level by adding deionized water at regular time intervals. The amount of water added was noted and this dilution factor taken into consideration during water analysis.

Mineral recoveries

Mass balances were performed from chemical analyses and mineral recoveries were calculated from measured product masses and mineral grades. During kinetic tests, recoveries of sulphide and gangue minerals for each fraction were determined. Based on the cumulative fractional recoveries, the modified Kelsall first order model with fast and slow-floating distribution was used for determining of the ultimate recovery and flotation rate constants according to the equation:

$$R_t = \left\{ R_\alpha - \varphi \right\} e^{(-K_f t)} + \varphi \left(e^{-K_s t} \right)$$

where R_t is the recovery of minerals at time t, R_α is the ultimate recovery, K_f and K_s are the fast-floating and slow-floating rate constants, and φ is the slow floating fraction. The kinetic parameters were estimated with a non-linear least squares fitter program utilizing a Nelder-Mead optimization routine. Results were also checked against the Solver routine found in Microsoft's Excel program.

For bulk flotation tests, only total sulphide and gangue mineral recoveries were determined after 10 minutes of flotation, assuming that ultimate recoveries, or close to that, were reached.

Water analyses

Water samples were taken of the feed water as well as water after milling. From these analyses, absorption and dissolution of ions during milling were determined. A detailed analysis of the water resources from the mine was performed. Only the most important ions are discussed.

Results and discussion

Particle size distribution after milling

Table II gives the particle size distribution of Rosh Pinah material milled at the plant and milled for 5 minutes in a laboratory batch rod mill.

It follows from Table II that a slightly different D_{50} value was obtained for the batch system compared to that of the plant material. Material milled during experimental work had a slightly narrower particle size distribution. This will give slightly better flotation performance than the plant, but it was assumed that the difference in particle size distribution would not have affected flotation and was minimal. For this investigation, a similar particle size distribution was used for each

flotation test. Therefore, particle size distribution effects were assumed to be negligible.

Water resources

Table III reveals the ion concentrations of water resources used during the investigation (circulation, lead thickener water, and borehole).

Table III shows that borehole water generally contained higher concentrations of ions associated with gangue minerals such as dolomite and muscovite (calcium, magnesium, potassium), while plant thickener water had more ions associated with sulphides (lead, zinc, copper). Cyanide was also mostly present in the plant thickener water (cyanide is added in the mill for sphalerite and pyrite depression). Borehole water contained the highest dissolved solids as well as sulphate and nitrate salt contents, whereas lead concentrate thickener water has the highest amount of total organic carbon as well as metal ions. The organic content was due to the presence of flocculant in the lead concentrate thickener water and excess xanthate in the lead tailing thickener water.

Froth stability

The frother was changed during later tests due to froth stability problems. During standard tests, the froth was stable and acceptable. Borehole water and thickener water contained high salt contents (see Table III) and this probably caused the unstable froth with Frother A. Frother B gave a stable froth even with salts present in the water.

Buildup of ions in circulating water

Figures 1 and 2 show the concentrations of ions in each of the 5 cycles of milling where mill water was circulated back. These are the measured ion concentrations for the laboratory milling system, which included adsorption or dissolution of ions from milled ore.

From Figure 1, it follows that calcium and magnesium (from dolomite) lowered in concentration in later cycles to 32–34 ppm, starting from 52 and 42 ppm, respectively. The pH of the final solution was 9.1 and this was favourable for some magnesium precipitation in the form of $Mg(OH)_2$ (Lascelles and Finch, 2001), although according to Fuerstenau and Fuerstenau (1982), a soluble $MgOH^+$ species could also be present.

It is not clear why some calcium was re-adsorbed during circulation, unless some calcium carbonate precipitate formed. The latter has a solubility of only 16 ppm in alkaline water (CRC, 1983). Considering the sulphate levels of the other water resources, then the majority calcium ions was most probably present as a sulphate, i.e. gypsum, which has a solubility of up to 2410 ppm in water (CRC, 1983). Other calcium species, such as $Ca(OH)^+$ and $Ca(OH)_2$, are expected

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Table II

Particle size distribution of Rosh Pinah material milled at the plant and in the batch mill

Distribution	Batch mill (μm)	Plant mill (μm)
D_{10}	3.22	2.26
D_{50}	44.64	38.50
D_{90}	122.97	165.99

Table III

Analyses of water resources

Ions	Circulated (ppm)	Pb tailing thickener (ppm)	Pb concentrate thickener (ppm)	Western borehole (ppm)	Eastern borehole (ppm)
pH	9.1	8.5	8.9	7.8	8.0
Ca	30	45	18	275	150
Mg	34	72	19	190	100
Na	31	120	180	400	135
K	57	24	8	25	50
Si	2.1	2.3	3.0	9	6.5
Cu	<0.05	17.2	30	0.05	0.05
Zn	<0.05	0.34	10	1.70	1.40
Pb	<0.05	0.33	0.50	0.40	0.20
Ag	<0.05	0.03	2.75	<0.01	<0.01
Fe	<0.05	0.09	0.12	0.40	1.40
Mn	<0.05	0.16	<0.03	0.70	2.20
Ni	<0.05	0.34	0.13	0.06	0.06
Ba	0.24	0.22	0.12	<0.01	0.07
Sr	0.33	0.48	0.27	5.00	1.34
Free CN	-	53	60	<0.01	0.15
Cl	ND	183	380	650	120
SO_4	ND	309	185	800	750
NO_3	ND	15	2	40	17
TDS	ND	949	825	2450	1400
TOC	ND	43	71	3	5

ND = not determined
TDS = total dissolved solids
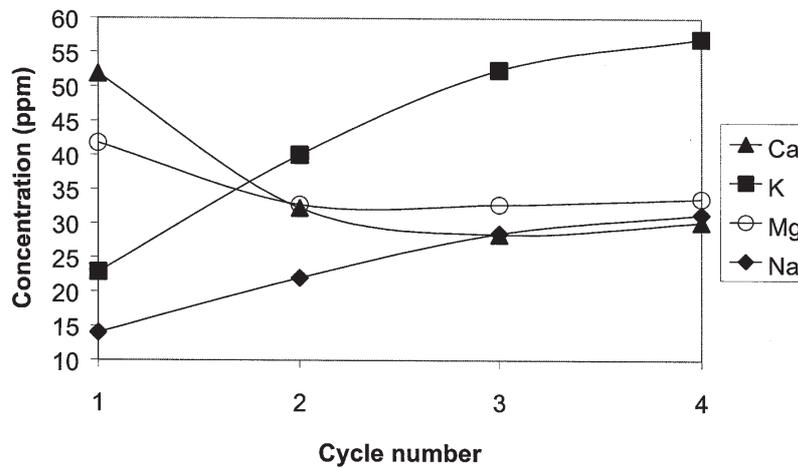TOC = total organic carbon

Figure 1—Concentration of calcium, potassium, magnesium, and sodium ions in circulated water
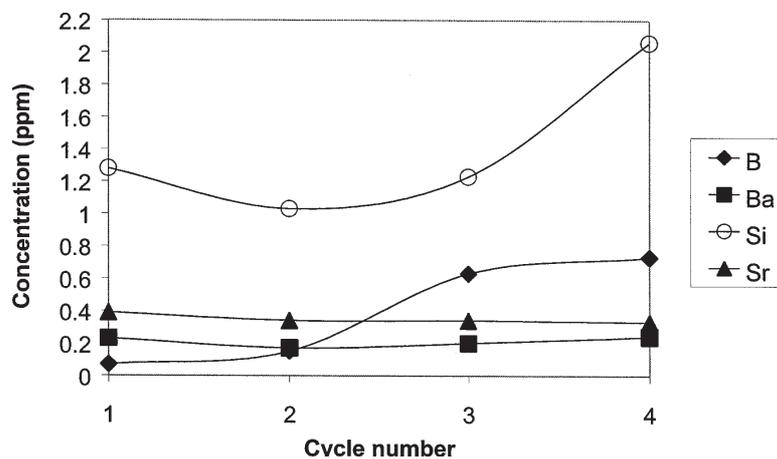

Figure 2—Concentration of boron, barium, silicon, and strontium ions in circulated water

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to occur, respectively, above pH 10 and 12 (Lascelles and Finch, 2001) and should therefore not be present. However, Allison (1982) indicated that metal hydroxides could still form at pH values below that at which precipitation of the hydroxide is calculated to begin. This was explained due to the continuing oxidation of the sulphide mineral, which would result in a local increase in the concentration of hydroxyl ions at or near the surface.

Other ions that increased in concentration were boron, potassium (from 23 to 57 ppm), silicon and sodium (Figures 1 and 2), while the concentrations of barium and strontium remained constant. Copper, lead and zinc ions did not build up in solution during the circulation and were below the detection levels of 0.05 ppm in all these cases.

Adsorption and dissolution of ions during milling and flotation

Ion concentrations were measured during milling and flotation tests in the presence of various water resources and metal ion solutions. Tables IV and V summarize the results obtained during these tests.

Water resources

Ions such as copper, lead, iron, and zinc from the various water resources were adsorbed on the ore and the solutions were either depleted of these ions or decreased in concentration during milling (see Table IV). One exception though was found with the lead concentrate thickener water where both copper and lead content increased after milling. In this case, copper ions increased from 30 ppm to 66 ppm, while lead ions increased from 0.5 to 3 ppm. In the case of the higher copper amount in solution, the 60 ppm free cyanide probably caused dissolution of copper from the surface of copper minerals and minerals that were activated with copper (galena, sphalerite and pyrite (Allison, 1982)) through formation of a soluble copper cyanide complex, such as $Cu(CN)_2^-$ and $Cu(CN)_3^{2-}$ (Seke and Sandenbergh, 2002). According to Leja (1982), lead cyanide forms an insoluble complex in water, although its solubility was not stated. Therefore, the lead ions present were probably either lead sulphate, $PbSO_4$, or lead hydroxide, $Pb(OH)_2$, with solubilities of 155 and 42 ppm (CRC, 1983), respectively. According to Ayres and co-workers (2002), lead hydroxide

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Table IV

Analyses of ions after milling and flotation in the presence of various water resources

Ions	Deionized		Pb tailing thickener		Pb concentrate thickener		Western borehole		Eastern borehole
	Milling (ppm)	Flotation (ppm)	Milling (ppm)	Flotation (ppm)	Milling (ppm)	Flotation (ppm)	Milling (ppm)	Flotation (ppm)	Milling (ppm)
Ca	86	70	60	55	84	78	203	117	191
Mg	55	39	82	52	75	47	130	78	136
Na	11	20	99	65	223	120	452	263	212
K	21	16	38	24	45	29	43	26	56
Si	1.41	6.31	1.04	1.90	2.06	1.33	1.68	2.83	1.74
Cu	<0.05	<0.05	6.5	2.34	66	25	<0.05	<0.05	<0.05
Zn	<0.05	1.14	<0.05	<0.05	0.28	<0.05	<0.05	<0.05	<0.05
Pb	<0.05	0.52	0.33	0.18	3.00	1.04	<0.05	<0.05	0.09
Fe	<0.05	3.32	0.06	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Mn	0.07	0.36	0.13	0.16	0.07	<0.05	0.09	<0.05	0.42
Ni	<0.05	<0.05	0.80	0.52	1.40	0.26	<0.05	<0.05	<0.05
Ba	<0.05	1.40	0.06	0.41	0.06	0.34	0.05	0.13	0.06
Sr	0.28	0.70	0.26	0.52	0.59	0.81	0.09	0.47	0.72

Table V

Analyses of ions after milling and flotation in the presence of various metal ions

Ions	Deionized	400 ppm Pb	800 ppm Pb	400 ppm Cu	800 ppm Cu (B)		58 ppm Zn (B)		115 ppm Zn (B)		230 ppm Zn (B)		916 ppm Zn (B)	
	Mill (ppm)	Mill (ppm)	Mill (ppm)	Mill (ppm)	Mill (ppm)	Float (ppm)	Mill (ppm)	Float (ppm)	Mill (ppm)	Float (ppm)	Mill (ppm)	Float (ppm)	Mill (ppm)	Float (ppm)
Ca	86	103	135	151	231	130	48	73	61	81	68	91	146	109
Mg	55	69	67	101	120	73	51	44	67	47	69	49	93	60
Na	11	15	12	11	13	23	20	29	19	33	17	31	19	26
K	21	23	24	24	24	16	32	23	35	26	30	21	33	21
Si	1.41	1.85	1.90	1.07	3.04	3.71	1.43	5.67	2.22	5.90	1.72	9.07	1.22	4.21
Cu	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	<0.05	<0.05
Zn	<0.05	<0.05	0.77	<0.05	0.25	<0.05	0.35	0.91	0.37	0.96	0.30	0.78	0.28	0.65
Pb	<0.05	0.05	<0.05	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.05	0.13	<0.05	0.13
Fe	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.40	0.47	0.37	0.70	0.28	0.60	0.25	0.34
Mn	0.07	0.39	1.34	0.94	2.27	0.36	0.08	0.13	0.08	0.21	0.12	0.13	0.43	0.18
Ni	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Ba	<0.05	0.11	0.09	0.07	<0.05	0.13	0.20	1.48	0.08	1.01	0.10	0.70	0.13	0.55
Sr	0.28	0.60	0.88	0.46	0.37	0.36	0.23	0.73	0.17	0.78	0.15	0.68	0.24	0.57

Mill = milling
Float = flotation

will only start to precipitate at a pH level between 8 and 10.5 and at concentration levels above 100 ppm. Below this level, lead will be present as dissolved metal.

It is known that silver ions can activate galena (Rykl, 1964) and this could probably cause the release of an equivalent amount of some lead in solution during milling with the lead concentrate thickener water. During flotation with xanthate and aeration, most of these ions probably formed complexes with xanthate and precipitated as metallic xanthates due to their low solubilities. For instance, the solubility product for silver propyl xanthate is 1.9×10^{-20} (Kakovsky, 1957). Precipitates of these xanthates can interfere with froth stability as well as inducing depression of valuable minerals. Therefore, it is pivotal to control the concentration of metal ions in flotation pulps. Metal ions in flotation pulps are also consuming unnecessary amounts of collectors dosed.

The elements associated with the gangue minerals, namely calcium, magnesium, sodium, and potassium, were all mainly released into the water during milling. A small amount of silicon (up to 6 ppm) was released from the ore during flotation in the case of deionized water, lead tailing thickener and Western borehole water. Metal ions probably replaced some surface silicon of quartz, activating its flotation behaviour. The opposite was found for the other water resources, where silicon was adsorbed during milling and flotation. Metal salts of lead, manganese (II) (Fuerstenau, 1975) and copper (Kraeber and Boppel, 1934) are known to activate quartz flotation at the considered pH level. Strontium ions were also found in borehole water with concentrations of up to 5 ppm. These ions tended to be either adsorbed or precipitated during milling and flotation. It is not known if xanthate will form any complex with strontium. However, Fuerstenau (1982a) indicated that a strontium salt (chloride) has no activation effect on sphalerite.

Ions

With the addition of lead and copper ions (Table V), significantly high amounts of calcium and magnesium ions, and silicon ions to a lesser extent, were released during milling from the surfaces of dolomite and quartz, respectively, although no evidence was found for zinc ions in solution. It is therefore expected that lead and copper ions will also activate these gangue minerals during sulphide flotation. The copper ions were probably present as $CuOH^+$ with the majority as a precipitate of $Cu(OH)_2$ at the considered alkaline conditions (Latimer, 1952). Copper hydroxide is extremely insoluble at a pH level of 8 with a solubility of only 0.001 ppm (Ayres, et al., 2002). These copper hydrolysis species can activate sphalerite through especially the $Cu(OH)_2$ precipitate (Wang, et al., 1989; Gerson, et al., 1999; Chen and Yoon, 2000). A similar analogy can be followed in the case of the lead hydroxide considering its concentration levels and pH sensitivity for precipitation as mentioned above.

There is approximately 3% manganese in the ore, which is mainly associated with dolomite and to a lesser extent to sphalerite and alabandite (MnS). A small amount of manganous ions (<2.50 ppm) (possibly present as $MnOH^+$ at alkaline conditions between pH 8 and 10 (Fuerstenau and Palmer, 1976)) was released into solution after milling in the presence of lead and copper additions, but the concentrations

dropped to below 0.4 ppm after flotation probably due to oxidation. According to Fuerstenau (1975), quartz can be activated with this manganous hydroxide during sulphonate flotation between pH values of 8 and 10, since quartz is negatively charged as determined with zeta potential measurements. It is not known whether a similar effect will occur during xanthate flotation and this should be investigated further.

During cases where zinc ions were added to the pulp (Table V), their concentrations mainly remained at constant levels of 0.3–0.4 ppm after milling, and this was slightly higher during flotation between 0.65 and 0.96 ppm. It is only observed at the high zinc ions concentration (115 to 916 ppm) that gangue ions such as calcium, magnesium and silicon (possibly present as $Si(OH)_6^{2-}$ at alkaline conditions between pH 8 and 10 (Fuerstenau, 1982b)) started to become more released into solution especially during flotation, indicating possible activation of the gangue minerals with zinc ions. The latter was probably due to zinc hydroxide precipitation that occurred during milling and flotation which has a solubility of only 0.3 ppm at pH 8.5 (Ayres, et al., 2002). It was also noted that silicon ions tended to be released even more during flotation up to 9 ppm. The flotation characteristics of these zinc activated Rosh Pinah minerals are not known and should be investigated further.

Flotation tests

Water resources

Figures 3 and 4 show upgrade ratios (with standard conditions as the base) and recoveries, respectively, obtained for minerals under consideration for a standard bulk flotation test and tests performed with circulated, lead concentrate thickener, lead tailing thickener and borehole water (Western and Eastern) (see Table III). The B in brackets indicates Frother B while no reference means Frother A was used.

During flotation with deionized (standard) water, the froth was stable because of the absence of salts in the water. Slightly higher gangue and significantly higher galena recoveries (30% enhancement), lower sphalerite (9.5% lower), and pyrite (26.6% lower) recoveries were obtained in the presence of Frother B. The sphalerite upgrade ratio also decreased to 0.86, whilst the galena upgrade improved slightly to 1.2. This again confirms the major influence of frother on recoveries and selectivities between minerals during flotation in the presence of various water resources.

With circulated water (see Table III), the upgrade ratios slightly decreased for most minerals compared to standard (B), but this parameter was equal to those obtained for the standard water source. The circulated water also improved galena recovery significantly to the same extent as found for the standard (B), i.e. 89.7%. Both recoveries of pyrite and sphalerite decreased somewhat.

Various water resources from Rosh Pinah mine (borehole and plant lead thickener water) resulted in an unstable froth as already mentioned. The effect can be seen from the results in Figure 4 where all the minerals had lower recoveries than the standard tests.

Lead concentrate thickener water had a major effect on both upgrade ratios as well as recoveries. The upgrade ratios improved for the valuable minerals, whilst their recoveries dropped simultaneously. This was probably due to the
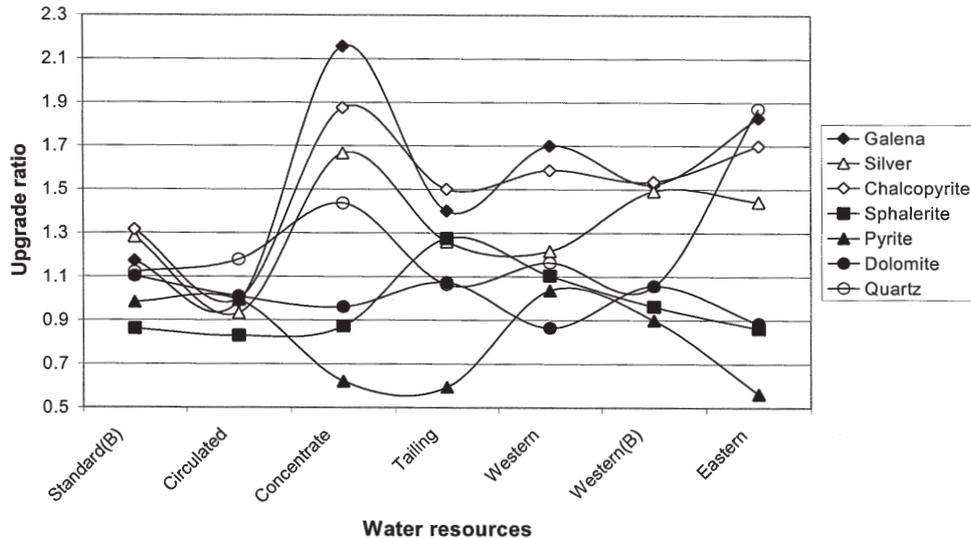
Figure 3—Mineral upgrade ratios in the presence of various water resources
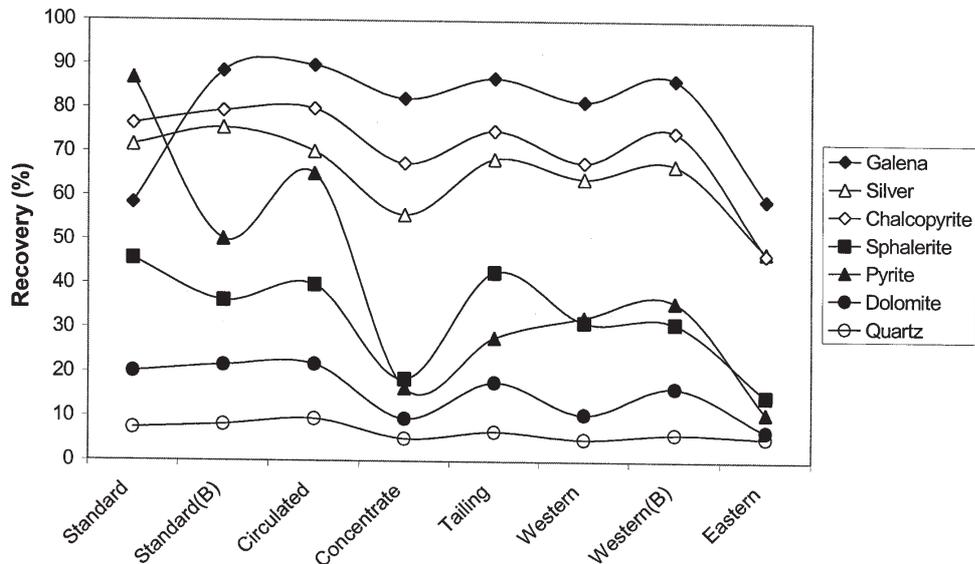

Figure 4—Mineral recoveries in the presence of various water resources

unstable froth that was encountered during utilization of this water source. In this case, for example, sphalerite and pyrite recoveries dropped to 18.5% and 16.5%, respectively. The latter phenomenon could be advantageous for selective galena/silver and copper mineral flotation despite the slight drop in their recoveries. The possible presence of free cyanide, as indicated previously, caused the depression of pyrite and sphalerite despite the unstable froth conditions and presence of copper, although the pH and E_h of the solution could have played a role. These latter conditions should be further investigated. The presence of zinc ions in the feed water (Table III), also probably contributed towards sphalerite depression (Fuerstenau, 1999).

Lead tailing thickener water also resulted in lower upgrade ratios and recoveries for pyrite (0.59 and 27.09%, respectively) compared to standard conditions, although the upgrade ratio slightly improved for galena (1.4). The

sphalerite recovery and upgrade ratio improved significantly to 42.7% and 1.28, respectively, in presence of this water source compared to the lead concentrate thickener water. Copper and cyanide ions were also present in this water, and could have caused activation of sphalerite through copper cyanide as demonstrated by Seke and Sandenbergh (2002).

The test with Western ore-field borehole water was repeated with Frother B. The advantage of this frother is that it gave a stable froth with borehole water where Frother A did not. It can be seen from the results that even with a stable froth for Western borehole water, lower mineral recoveries were obtained than for the standard test, except for galena (upgrade ratio 1.7 and 86.5% recovery). Therefore, salts in the borehole water probably enhanced selectivity for galena at the conditions investigated. This is beneficial since selective flotation of galena can thus be obtained with this borehole water, but an additional depressant, such as

cyanide, will be needed to decrease sphalerite and pyrite flotation. It is not clear what could have caused the flotation behaviour of sphalerite and pyrite, although nearly similar results were obtained during standard flotation conditions where no activation was induced.

Eastern borehole water resulted in similar disastrous results for all minerals as obtained for lead concentrate thickener water. In this case, even the lead recovery dropped significantly to 59.2%, similarly as those obtained for the standard water test. It is not clear whether the lower recoveries were due to either depression of minerals or the unstable froth itself or a combination of both. However, this water contained the highest manganese, potassium and iron ions concentration of the water resources investigated and which one of these ions, or combination thereof, depressed galena is not known. If it is determined what salts caused the depression of the other minerals without depressing galena it could be added to the lead flotation circuit. It seems, therefore, that this water resource should not be used during galena flotation at the Rosh Pinah plant due to its negative effects, unless a suitable frother can be employed in future.

Flotation of quartz was not enhanced despite evidence of metal ions activation and release of silicon ions in solution. However, the activation effect could be negligible and was also probably masked during flotation of galena and other minerals.

Kinetic flotation tests were performed during galena flotation in the presence of various water resources in order to evaluate various kinetic parameters. Figures 5 to 11 give the recoveries of various minerals, such as galena, silver, copper minerals (chalcopyrite/bornite/tennantite), sphalerite, pyrite, dolomite, and quartz, respectively, over a flotation period of 10 minutes.

Table VI gives the flotation kinetic modelling results obtained for these minerals using the modified Kelsall model. All the models had a regression fit of better than 99.9%. These parameters are used to describe selectivity against gangue or unwanted minerals in the galena circuit. Since the feed material contains 89% gangue (Table I), selectivity against these minerals is as important as that of the valuable minerals because selectivity is obtained by changing the kinetics of the gangue.

For pyrite, the fast floating fractions increased significantly up to 64% for all water resources used, although its recoveries dropped dramatically in the presence of both lead concentrate (18.98%) and tailing thickener water (29.45%). The decrease in pyrite for the latter water resources was due to cyanide depression as stated above. For dolomite, the circulating water decreased the fast floating rate, whereas lead tailing thickener water increased this kinetic parameter. The latter water resource also improved this parameter in the case of quartz, but its ultimate recovery decreased dramatically.

For silver, copper minerals, and sphalerite, the lead concentrate thickener water seems to have boosted the fast floating fractions, but the ultimate recoveries were negatively affected, although the slow floating rate improved for silver. In the case of dolomite, only the ultimate recovery was negatively affected through employing this water source.

In order to evaluate any change in galena selectivity, based on kinetic parameters, induced through utilizing the abovementioned three water resources, two different kinetic ratios were evaluated, i.e. slow floating rates and fast floating fractions. Fast floating rates are not considered because they have no significant and practical effect on a plant unless an order of magnitude change occurs. The ratios were based in terms of the kinetic parameters obtained with deionised water as the base case for each mineral. The results, which were based on the parameters summarized in Table VI, are illustrated in Figures 12 and 13.

The objective here is to improve galena selectivity against other minerals in the presence of these water resources. Ratios above unity indicate unwanted activation (except in the case of galena, silver and copper minerals where it would
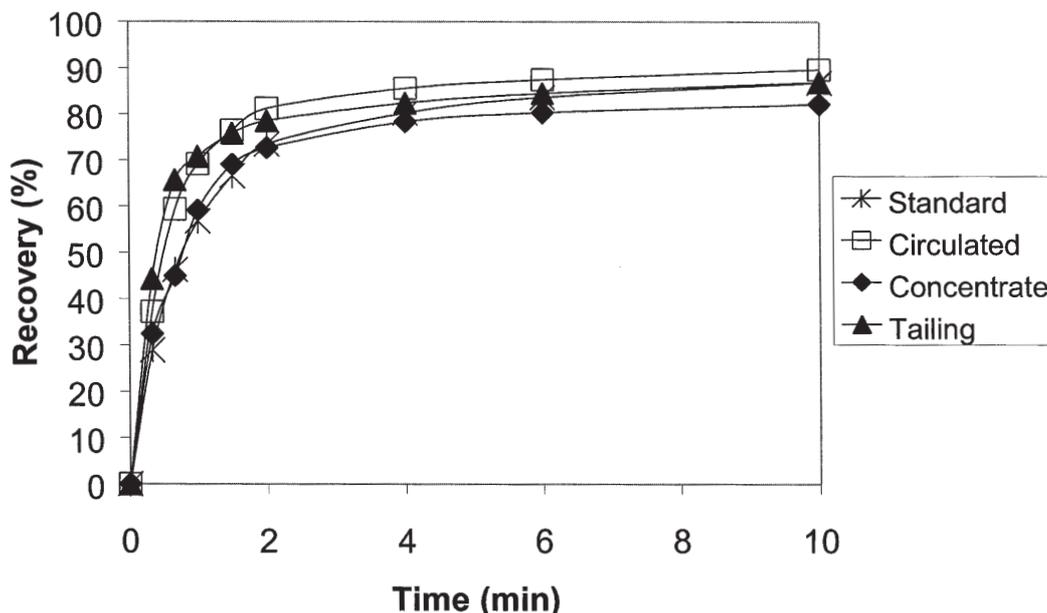

Figure 5—Galena recovery for tests with standard, circulated, lead concentrate and lead tailing thickener water
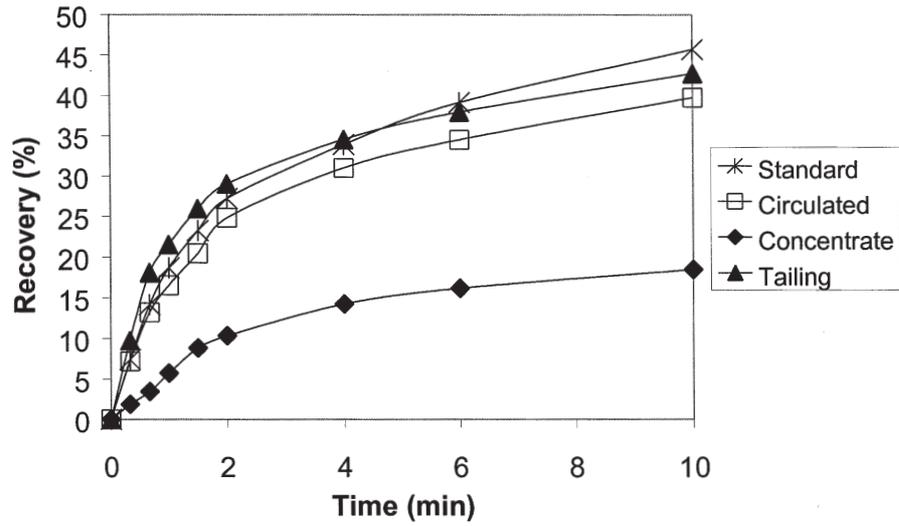
Figure 6—Sphalerite recovery for tests with standard, circulated, lead concentrate and lead tailing thickener water
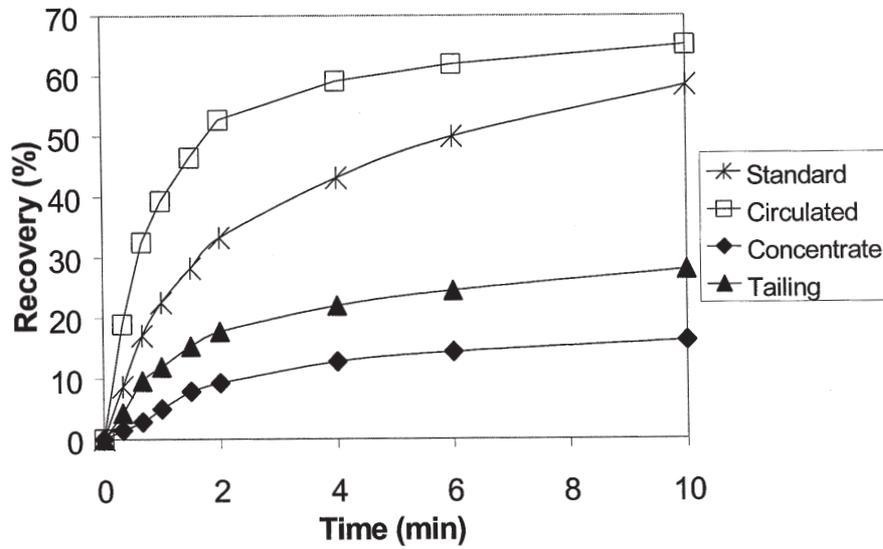

Figure 7—Pyrite recovery for tests with standard, circulated, lead concentrate and lead tailing thickener water

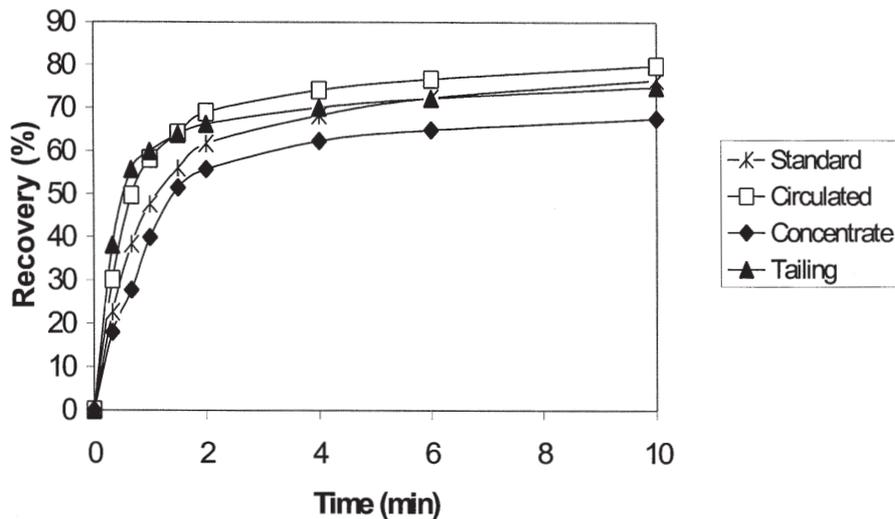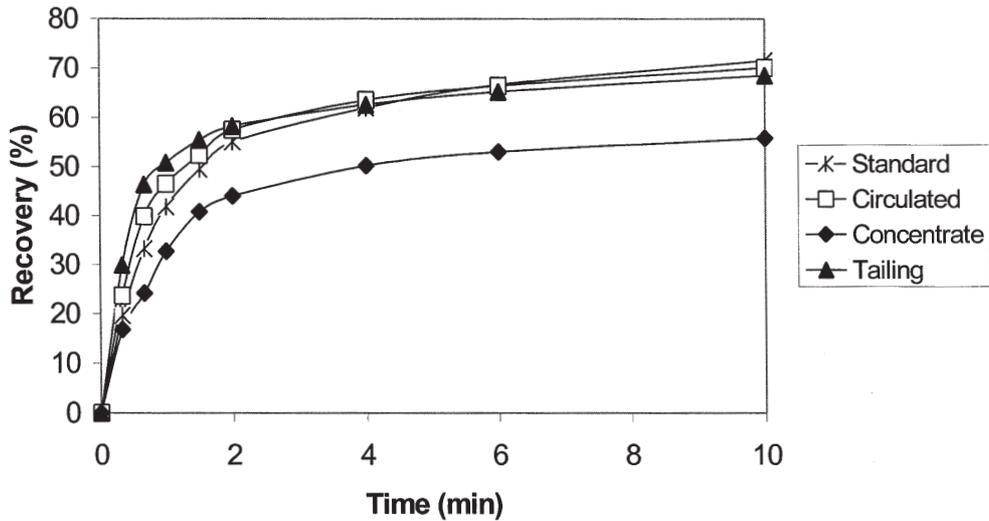**Figure 8—Copper mineral (chalcopyrite/bornite) recovery for tests with standard, circulated, lead concentrate, and lead tailing thickener water**

Figure 9—Silver recovery for tests with standard, circulated, lead concentrate, and lead tailing thickener water
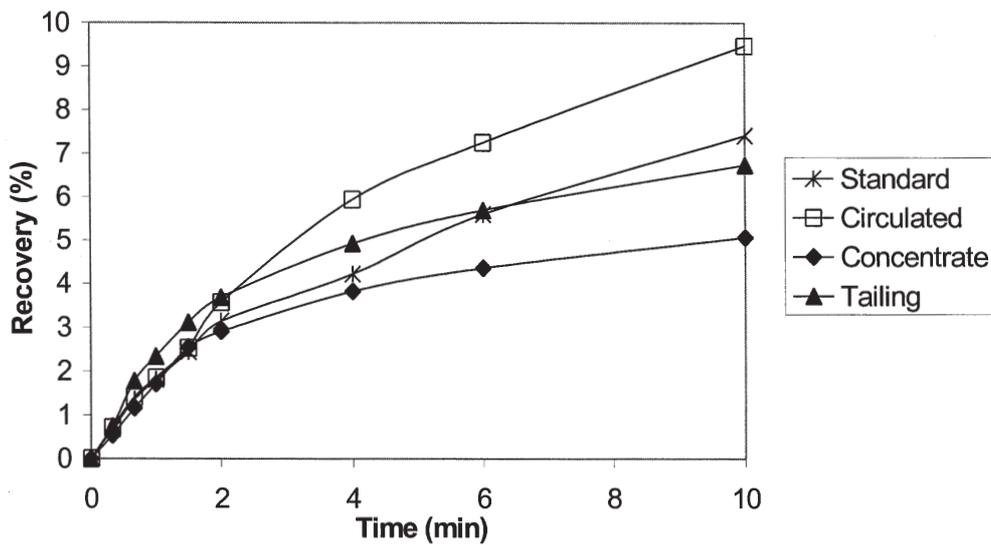

Figure 10—Quartz recovery for tests with standard, circulated, lead concentrate and lead tailing thickener water
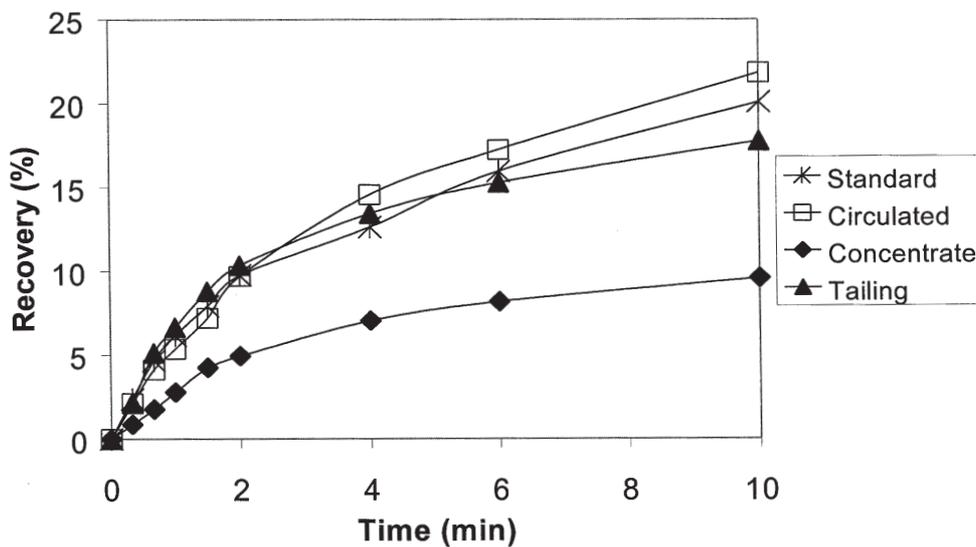

Figure 11—Dolomite recovery for tests with standard, circulated, lead concentrate and lead tailing thickener water

Influence of water resources and metal ions on galena flotation of Rosh Pinah ore

Table VI

Modified Kelsall model values for various minerals during galena flotation

Water source	R_a (%)	φ_s	φ_f	K_s (min^{-1})	K_f (min^{-1})
Galena					
Deionized	89.94	0.27	0.73	0.07	1.39
Circulated	92.40	0.18	0.82	0.08	1.88
Pb concentrate	85.77	0.23	0.77	0.04	1.48
Pb tailing	87.48	0.24	0.76	0.07	2.67
Ag					
Deionized	73.18	0.45	0.55	0.07	1.40
Circulated	71.00	0.38	0.62	0.06	1.64
Pb concentrate	58.24	0.27	0.73	0.11	1.18
Pb tailing	67.96	0.39	0.61	0.05	2.34
Chalcopyrite/bornite					
Deionized	78.53	0.37	0.63	0.05	1.33
Circulated	81.24	0.33	0.67	0.04	1.77
Pb concentrate	72.06	0.14	0.86	0.05	0.98
Pb tailing	74.49	0.35	0.65	0.03	2.59
Sphalerite					
Deionized	48.21	0.32	0.68	0.06	0.61
Circulated	42.01	0.32	0.68	0.07	0.67
Pb concentrate	21.49	0.26	0.74	0.01	0.40
Pb tailing	43.22	0.25	0.75	0.07	0.88
Pyrite					
Deionized	62.92	0.63	0.27	0.14	1.05
Circulated	67.56	0.36	0.64	0.05	1.23
Pb concentrate	18.98	0.44	0.56	0.11	0.43
Pb tailing	29.45	0.43	0.57	0.11	0.87
Dolomite					
Deionized	23.00	0.25	0.75	0.07	0.26
Circulated	23.48	0.25	0.75	0.07	0.17
Pb concentrate	10.89	0.25	0.75	0.07	0.26
Pb tailing	19.35	0.24	0.76	0.07	0.43
Quartz					
Deionized	11.29	0.19	0.81	0.02	0.15
Circulated	12.24	0.12	0.88	0.04	0.18
Pb concentrate	6.32	0.19	0.81	0.06	0.35
Pb tailing	8.36	0.19	0.81	0.06	0.33

Where:

R_a -   Predicted ultimate recovery
φ_s -   Slow floating fraction
φ_f -   Fast floating fraction
K_s -   Slow floating rate constant
K_f -   Fast floating rate constant.

be beneficial), whereas ratios below unity will indicate depression.

Regarding slow floating rate ratios, $k_s/(k_s$ (deionized)) (Figure 12), selectivity increased for quartz for all water sources evaluated, which is unwanted. When employing lead concentrate thickener water, selectivity against the slow floating rates of pyrite, galena (unwanted) and sphalerite improved, but selectivity improved for silver. Selectivity against pyrite was obtained for all these water resources, which is favourable.

Regarding fast floating fraction ratios (Figure 13), selectivity for pyrite increased significantly in the presence of all water resources, which is unwanted. The lead concentrate thickener water improved this selectivity for copper minerals as well as for silver.

Another way to evaluate galena flotation selectivity is to determine theoretical grade-recovery relationships from the kinetic parameters over a 10 minute flotation period in the presence of various water resources. This was accomplished through considering sphalerite, pyrite, dolomite and quartz as the gangue minerals during galena flotation. The obtained parameters in Table VI were re-entered into the modified Kelsall model and theoretical grades calculated considering the feed grade of each mineral. Figure 14 gives the results obtained for the galena grade-recovery relationships.

It follows from Figure 14 that lead concentrate thickener water resulted in the highest galena grade-recovery relationship and therefore good galena selectivity against gangue minerals was obtained. This is valid especially for galena recoveries below about 85%. Above a recovery of
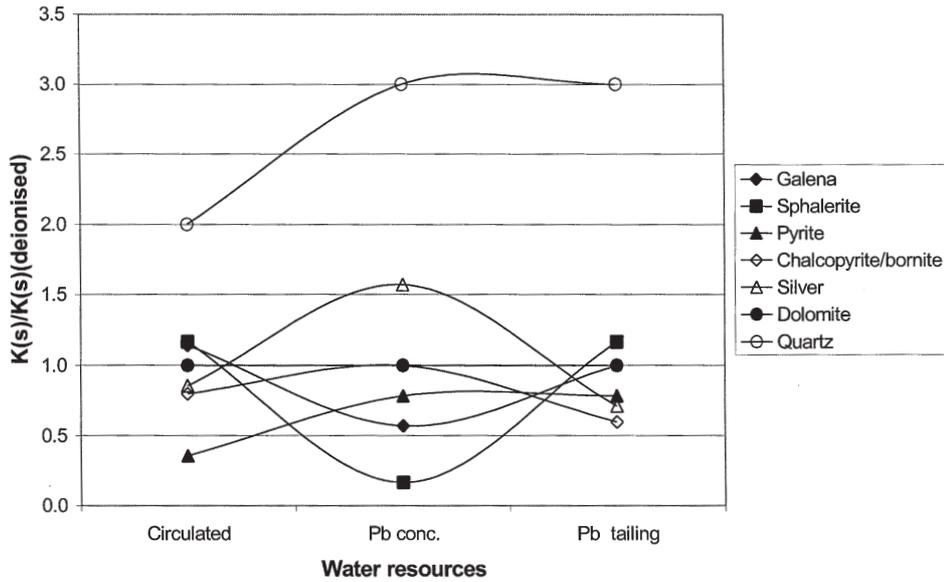
Figure 12—Slow floating rate selectivities for various minerals in the presence of various water resources
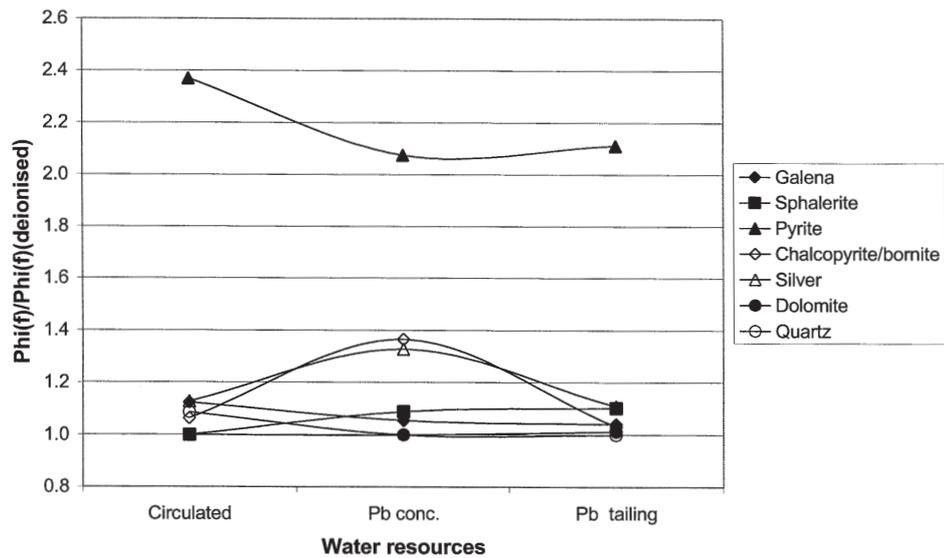

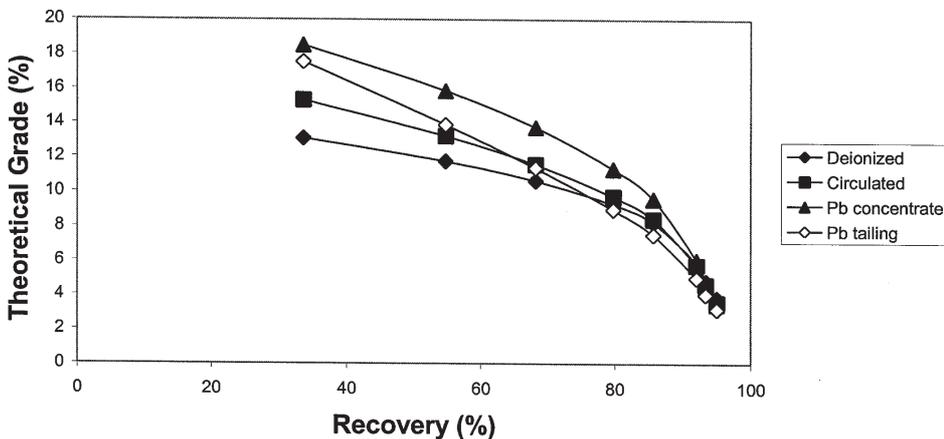**Figure 13—Fast floating fraction selectivities for various minerals in the presence of various water resources**

Figure 14—Theoretical galena grade-recovery relationships in the presence of various water resources

85%, the grades decreased significantly, which probably was due to mechanical entrapment of fine dolomite and quartz—no cleaner stages were introduced during the laboratory flotation tests. The latter was also further affected through the relatively high recoveries of sphalerite and pyrite (Table VI). Lead tailing thickener water seems to have the most negative effect in the 80% galena recovery region. Overall, deionized water resulted in the worst galena selectivity.

Ions

The effect of various additions of ions, such as lead, copper, and zinc, during galena flotation, was also evaluated and recovery and upgrade ratio (standard as base case) results are shown in Figures 15 and 16.

Lead nitrate, at a lead concentration level of 400 ppm, caused an unstable froth with Frother A and this combination seemed to have improved selectivity against sphalerite, pyrite

and even dolomite, although no free lead ions were noticed in the flotation pulp. However, recoveries of galena/silver and copper minerals (denoted as chalcopyrite) were unaffected, and this is positive. Therefore, improved selectivity for galena and its associated minerals were obtained, at least at this concentration level, although sphalerite upgrade ratio improved to 1.6. No E_h measurements or surface species analysis were performed in order to understand this phenomenon.

At a lead concentration of 800 ppm, and in the presence of Frother B, a stable froth was obtained. In this case, similar results were obtained than with the standard condition as well as in the presence of Frother A, except the sphalerite recovery improved from 43.1% to 69.5% compared to the standard case, although the upgrade ratio decreased slightly to 1.3. Overall, it is again confirmed that lead ions can activate sphalerite flotation, although it seems to be
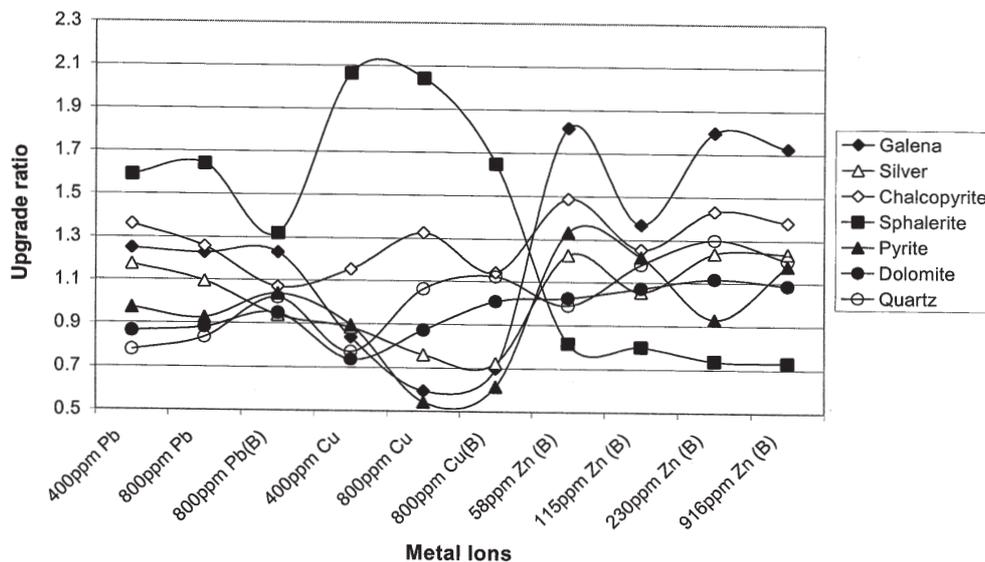

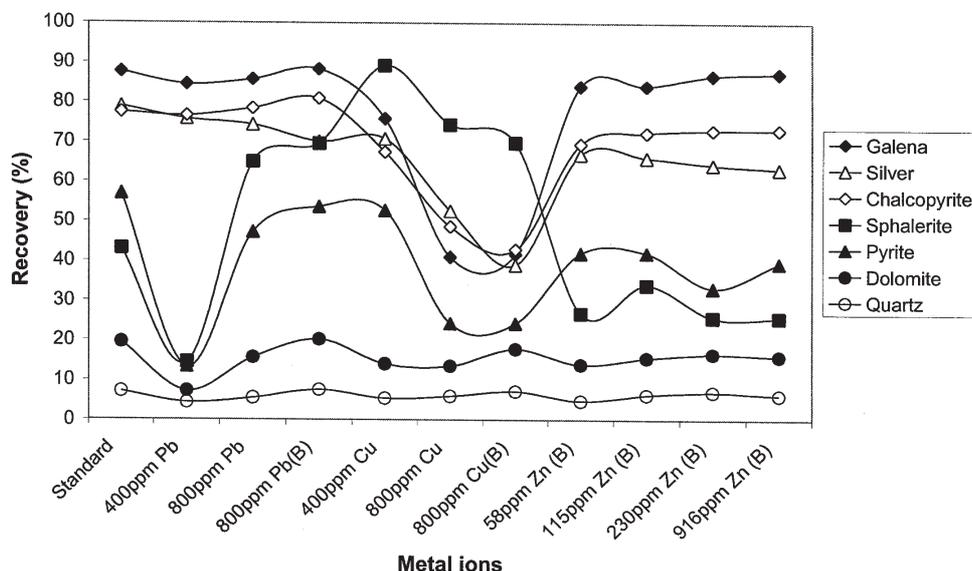Figure 15—Mineral upgrade ratios in the presence of various metal ions

Figure 16—Mineral recoveries in the presence of various metal ions

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dependent on the lead concentration utilized during flotation while frother type seems to play no role. The recovery and upgrade ratio of silver also dropped somewhat in the presence of Frother B. In the case of chalcopyrite, the recovery increased slightly, whereas its upgrade ratio decreased simultaneously. The upgrade ratios of dolomite and quartz increased slightly to levels similar to those achieved at the standard conditions in the presence of Frother B. No evidence was found for gangue mineral activation with lead ions during galena flotation, despite the higher amount of gangue ions that reported in the flotation pulp water previously described.

Copper sulphate additions caused an unstable froth with Frother A. The most significant sphalerite activation (89% recovery and 2.09 upgrade ratio) reported for 400 ppm copper addition during unstable froth conditions, while at 800 ppm, sphalerite recovery was significantly lower at 73%. The test with addition of 800 ppm copper was repeated with Frother B and resulted in a stable froth. A higher sphalerite recovery (69.8%) than the standard test (43.1%) was obtained at these conditions, whilst, in general, recoveries remained constant for the different frothers employed. Thus, it was again confirmed that the different frothers employed played a negligible role. The exception was found for silver minerals where recoveries decreased significantly with 14% in the presence of Frother B, which is unwanted. Dramatically lower recoveries also reported for galena, silver, pyrite, and copper minerals at addition levels of 800 ppm copper than at 400 ppm. It seems, therefore, that in the presence of a 800 ppm copper concentration, the sulphide minerals were depressed to a certain extent, but the mechanism of depression, especially for galena and copper minerals, is uncertain. However, no excess copper sulphate reported in the pulp solution (Table V) where froth viscosity, and therefore selectivity, could have played a role during flotation. Thus, this effect can probably be ascribed to the presence of high concentrations of copper hydroxide precipitates on mineral surfaces. Also noteworthy, is the relatively high sphalerite upgrade ratios (about 2) and relatively low galena, silver, and pyrite upgrade ratios obtained during copper addition. Dichmann *et al.* (2001) found that copper ions depressed pyrite in the presence of sphalerite because the copper favoured sphalerite over pyrite and this occurred the strongest at pH values between 6 and 9.5. Furthermore, the collector (SNPX) should have favoured copper activated sphalerite over pyrite due to a higher affinity for copper xanthate formation as is evidenced through its lower solubility product found with the former (Leja, 1982). They also indicated that it appeared that competition favoured sphalerite over pyrite if there was a shortage of either collector or copper ions, and this competition was not evident when both reagents were restricted or in excess. Surface studies are needed to elucidate this mechanism. Again, no evidence was found for gangue mineral activation with copper ions during galena flotation, despite the higher amount of gangue ions that reported in the flotation pulp water previously described.

Flotation tests with addition of zinc sulphate were all performed in the presence of Frother B and all had stable froths. In this investigation, zinc ions caused depression of sphalerite as expected during flotation and it seems to have occurred successfully at the low zinc levels investigated (58 ppm), while the recovery remained fairly constant even at higher zinc concentrations. Sphalerite recovery was depressed to a low level of 25% with only zinc ions present with an upgrade ratio of 0.8. There was a slight depression of the other minerals but not as strong as for sphalerite. The exception was galena recovery, which remained constant at 84 to 88%. This can be utilized advantageously in the lead flotation circuit at the plant in combination with cyanide. Slightly lower recoveries were obtained for copper minerals (chalcopyrite), silver and pyrite compared to the standard conditions, but their upgrade ratios varied. It seems that there was a slight enhancement of dolomite and quartz upgrade ratios, although recoveries were unaffected. This was due to zinc activation as stated previously.

Conclusions

It was found during this investigation that metal ions and salts content of plant water influenced the flotation behaviour of Rosh Pinah milled material as well as the froth stability. The water resources from Rosh Pinah mine caused activation and depression effects of minerals in the ore depending on the composition of the water. All the water with a high salt content, such as borehole water, decreased the froth stability if a weak frother was used.

The various water resources employed during galena flotation caused activation, depression or selectivity effects on minerals due to the presence of different ions in solution. Metal ions in these water resources were adsorbed by the ore, whilst ions associated with gangue minerals were released into the flotation pulp.

Lead concentrate thickener water:
➤ depressed sphalerite and pyrite due to the presence of cyanide and zinc ions (to a lesser extent)
➤ increased fast floating fractions for silver and copper minerals and sphalerite, but ultimate recoveries were negatively affected
➤ enhanced slow floating rate selectivity against pyrite and sphalerite
➤ resulted in highest galena grade-recovery selectivity.

Lead tailing thickener water:
➤ enhanced sphalerite recovery during galena flotation (unwanted) due to the presence of copper cyanide complexes
➤ increased fast floating fractions of pyrite up to 64%, although recoveries dropped due to cyanide depression
➤ caused most negative effect in the 80% galena grade-recovery region.

Western borehole water did not affect galena recovery, but sphalerite and pyrite recoveries were unacceptably too high. Eastern borehole water decreased mineral recoveries significantly and should be used with a suitable frother.

Ions from copper, lead, and zinc salts tended to release ions, such as calcium, magnesium, silicon, and manganese (especially with copper and lead ions) from gangue minerals (dolomite, quartz and minor amounts of alabandite) during milling, although these metal ions were not detected in solution due to adsorption and/or precipitation on mineral surfaces.

Influence of water resources and metal ions on galena flotation of Rosh Pinah ore

During galena flotation, lead ions depressed sphalerite, pyrite and dolomite at a lead concentration of 400 ppm, but sphalerite was activated at a concentration of 800 ppm with a recovery of 69.5% and upgrade ratio of 1.3. Sphalerite was activated with 400 ppm copper ion concentration (89% recovery, 2.09 upgrade ratio), slightly depressed at 800 ppm copper ion concentration (73% recovery). A similar tendency was found for the other sulphide minerals under consideration. These effects were ascribed to copper hydroxide formation on the surfaces of these minerals that affected their flotation behaviour. Sphalerite was depressed with zinc ions (maximum recovery of 25%, 0.8 upgrade ratio). These findings correspond with those in previous investigations. Dolomite and quartz were slightly activated with zinc ions. No evidence was found that lead and copper ions activated any gangue minerals during galena flotation, despite the higher amount of gangue ions that reported in the flotation pulp water. Results indicated that the frother type employed played a negligible role during galena flotation in the presence of these metal salts.

In plant operations, it will be necessary to isolate each ion in the water resource and determine its effect on minerals in the ore, as well as the interaction of ions on each other. Only then can the full benefit of water resources be obtained and detrimental ions then removed from the water resource.

Acknowledgements

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