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The effect of temperature on the flotation of pyrite

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SYNOPSIS

In the investigation described here, it was found that the main effect of temperature is on the rate of flotation, and that adsorption of the reagent is not rate controlling. Above 10°C, the flotation rate of pyrite and gangue increases almost exponentially with a rise in temperature. Below that temperature, the flotation rate of pyrite shows a sudden marked decrease, that of gangue increases, and the sulphur grades are significantly poorer.

In the flotation of pyrite, the mass transfer of the pyrite from the pulp to the froth is thought to be the rate-controlling step, whereas the flotation of gangue is controlled by the combined effect of the stability and velocity of the froth and the viscosity of the elutriating medium. The latter is probably the controlling effect at temperatures below 10°C.

Little difference was noted in the recoveries (provided no time limit was set) with changes in temperature; hence adequate recoveries can be obtained at low temperatures by the introduction of longer residence times for the pulp. The adverse effects of low temperatures on grades can be overcome only by additional cleaning or by heating of the pulp.

SAMEVATTING

Daar is in die ondersoek wat hier beskryf word, gevind dat die vernaamste uitwerking van temperatuur is dat dit die flottasietempo raak en dat die reagentsabsorpsie nie tempobeherend is nie. Bo 10°C versnel die flottasietempo van piriet en aarsteen byna eksponensiaal met 'n styging in temperatuur. Onder hierdie temperatuur toon die flottasietempo van piriet 'n skielike duidelike afname, terwyl dié van die aarsteen toeneem en die swawelgrade beduidend laer is.

In die flottasie van piriet word daar gereken dat die massa-oordrag van die piriet van die pulp na die skuim die tempobeherende stap is, terwyl die aarsteenflottasie beheer word deur die gekombineerde uitwerking van die stabiliteit en snelheid van die skuim en die viskositeit van die elutrieermiddel. Laasgenoemde is waarskynlik die beherende faktor by temperature onder 10°C.

Daar is min verskil in die herwinnings waargeneem met 'n verandering in temperatuur (mits daar geen tydgrens gestel word nie); gevolglik kan toereikende herwinnings by laer temperature verkry word deur langer residensietye vir die pulp te gebruik. Die nadelige uitwerking van lae temperature op grade kan net oorkom word deur verdere skoonmaak, of deur die pulp te verhit.

Introduction

On various flotation plants in the Orange Free State, the monthly recovery of pyrite correlates closely with the ambient temperature (Fig. 1). This correlation is due to several factors, one of which may be the effect of temperature on the flotation process. Experience has shown that, during the winter months, significant problems in terms of grade and recovery are experienced in the flotation of pyrite on the goldfields of the Witwatersrand and the Orange Free State.

Temperature is known to affect the kinetics of flotation, since an increase in temperature reduces the induction time required[1] but often results in poorer selectivity[2]. This has been observed particularly for fluorspar[3] and for mixtures of sphalerite and chalcopyrite[4]. Temperature also affects the pH value[5] and the viscosity of the pulp[6], as well as the formation of bubbles[7]. The temperature of the pulp affects the stability of the froth[8] since, the lower the temperature, the more stable is the froth. The effects of temperature on the kinetics of reagent adsorption have been studied extensively, much of the work being concentrated on temperatures higher than ambient[9–11], at which the rate of adsorption is higher, although desorption is often enhanced[10].

In the present study, the effects of temperature on the rate of pyrite flotation, on the adsorption of the collector, and on the physical characteristics of the pulp and froth phases are examined.

Experimental Work

The ore used, which was a typical feed to a pyrite flotation plant in the Orange Free State, had a sulphide sulphur content of 1,0 to 2,0 per cent. At least 75 per cent of the

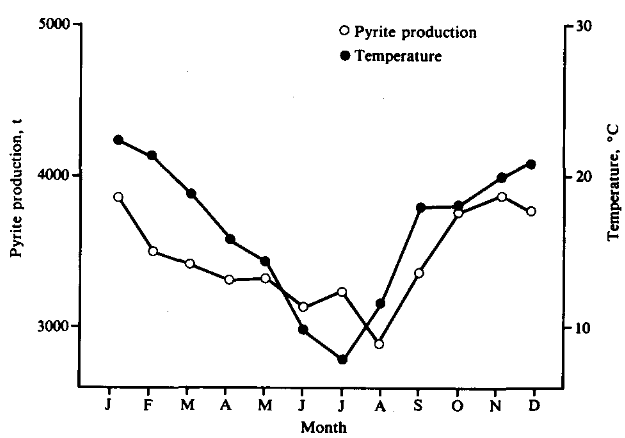

Fig. 1—Relation between monthly pyrite production and temperature

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TABLE I

REPRODUCIBILITY OF PYRITE FLOTATION AT 23°C

Float no.	Cumulative recovery at various times, %						ψ	$k \times 10^2 s^{-1}$
	15 s	30 s	60 s	120 s	240 s	420 s	%	
1	38,63	55,62	70,93	81,05	86,77	89,40	91,40	7,77
2	39,94	56,10	70,37	81,10	87,35	90,31	91,67	7,88
3	38,57	55,45	70,35	79,83	86,15	88,97	90,57	7,83
s	0,78	0,34	0,32	0,72	0,60	0,68	0,57	0,06

ψ = 'Infinite-time' recovery, i.e. recovery for which no time limit was set
k = Rate constant
s = Standard deviation

feed particles were smaller than 75 μm, and approximately 65 per cent were smaller than 38 μm. The ore was not leached with acid before being floated since initial studies had indicated that this reduces the recovery of pyrite. The batch flotation studies were carried out in a Leeds flotation cell, the design of which had been altered so that the cell could be housed in a temperature-controlled water-bath. After a few changes in the design of the cell, highly reproducible results were obtained, as shown in Table I.

Two modes of operation were employed: one in the presence of a froth phase, and the other in its virtual absence. In the former mode, a froth height of 2,5 cm was maintained by the constant addition of water to the cell; in the latter, the froth height was below 0,5 cm, which gave a close simulation of flotation in the absence of a froth phase. The collector, sodium mercaptobenzothiazole (SMBT) was added at 40 g/t, and the frother, triethoxybutane (TEB), at 12 g/t. The pH value was set at 4,0 by the use of lime, the natural pH value of the pulp being approximately 3,6. The temperatures were maintained constant to within 1,0°C. The ore was conditioned for 4 minutes after the addition of the collector, and for a further 1 minute after the addition of the frother. The solids content of the pulp in all the tests was 30 per cent. Six concentrates were collected, and Klimpel's model[12] was used in the analysis of the results. All the runs were repeated several times to ensure reproducibility of the results, and sulphur assays were checked routinely by the Analytical Science Division at the Council for Mineral Technology (Mintek).

Adsorption studies were carried out on a continuously stirred tank reactor containing the collector solution. The fraction of ore between 38 and 106 μm was added at time zero, and the solution was pumped via a 4 μm sintered stick to an ultraviolet spectrophotometer for continuous monitoring of the collector concentration. In this way, information on kinetic and pseudo-equilibrium adsorption were obtained. Batch tests were also done so that adsorption isotherms could be plotted.

Results

The effect of temperature on the recovery of pyrite is shown in Fig. 2, and Fig. 3 illustrates the effect of temperature on the rate constant, *k*, as derived from Klimpel's model[12] (considered to be pseudo first order) for the two modes of operation.

Fig. 4 shows the rate constants for the flotation of the gangue at various temperatures. The froth can be seen to be more stable and its velocity significantly lower at temperatures below 20°C.

Recovery for an unlimited time, i.e. 'infinite-time' recovery (ψ), of pyrite and gangue at various temperatures is shown for both operational modes in Fig. 5, and plots of grade versus recovery at three temperatures are given in Fig. 6 for these two modes of operation.

Adsorption isotherms determined over the range of temperatures under investigation are shown in Fig. 7. The pseudo-equilibrium time for adsorption was considered to be 15 minutes.

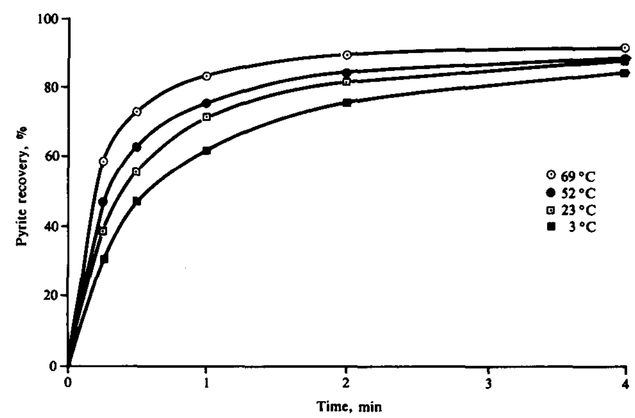

Fig. 2—Effect of temperature on pyrite recovery

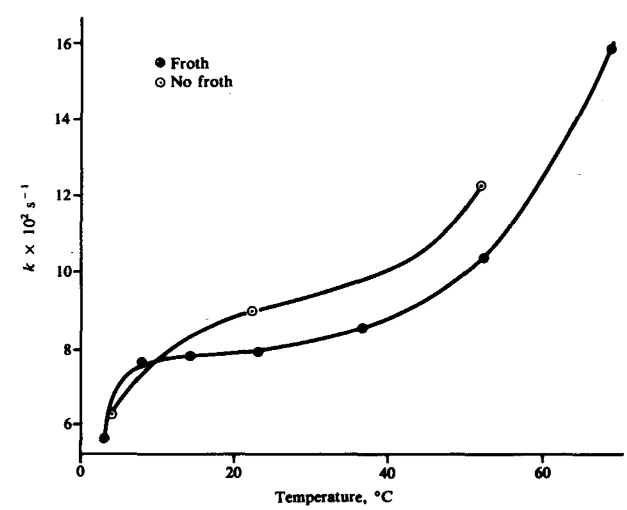

Fig. 3—Effect of temperature on rate of pyrite flotation

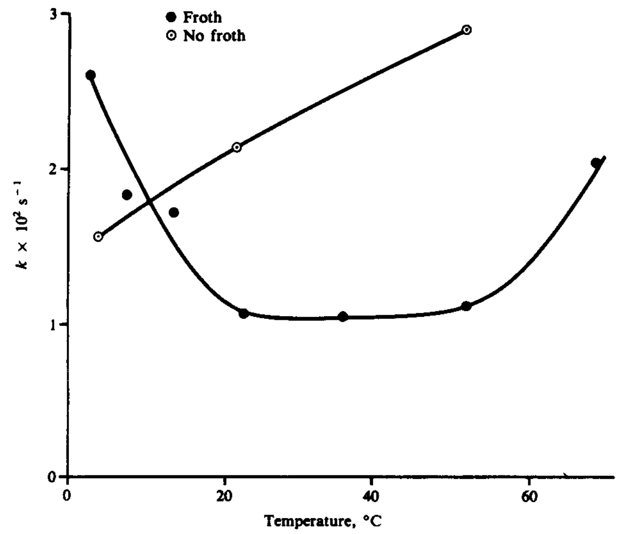

Fig. 4—Effect of temperature on rate of gangue flotation

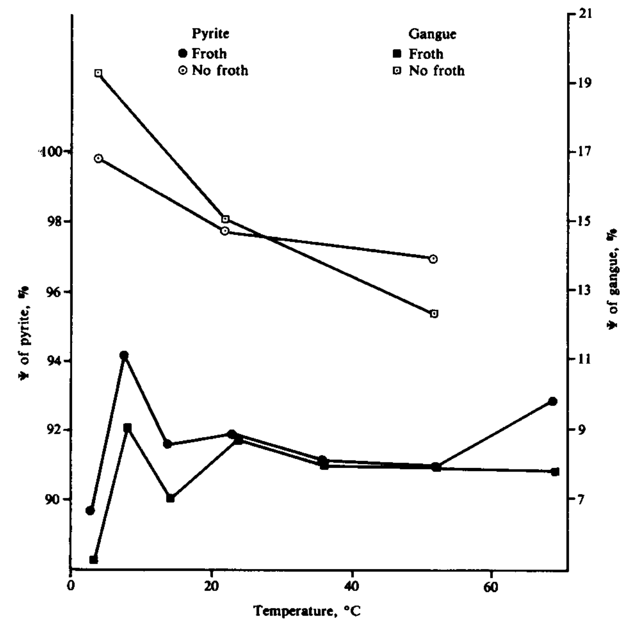

Fig. 5—Effect of temperature on 'infinite-time' recovery (ψ) of pyrite and gangue

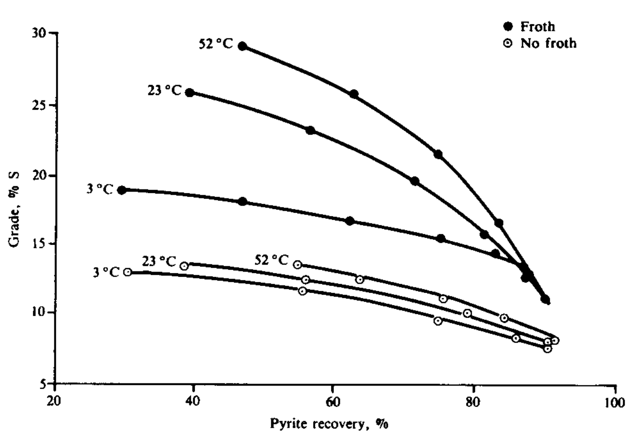

Fig. 6—Grade versus recovery at different temperatures and modes of operation

Fig. 8 gives the results of the tests on froth stability. For these tests, the time taken for the froth to break down from its maximum height to a predetermined height (termed duration and measured in seconds) was measured at different temperatures. Also shown are similar results obtained on a two-phase froth by Götte[13] using sodium dodecyl sulphate as frother.

The results of varying reagent concentrations, aeration rates, and impeller speeds are presented in Tables II to VII.

As can be seen from Tables II to V, variation in the concentrations of the flotation reagents had little significant effect on the rate of flotation or on the infinite-time recoveries of pyrite.

However, as Tables VI and VII indicate, variations in the aeration rate and the impeller speed had a significant effect on the infinite-time recovery and flotation rate of pyrite.

Fig. 9 shows the effect of temperature on the viscosity of pulps of different densities. These tests were carried out with a Störmer viscometer. Also shown is a plot for which Mooney's correlation for pulps[14] was used:

$$\ln \frac{\mu_m}{\mu_l} = \frac{2{,}5\phi_s}{1\text{-}c\phi_s},$$

where μ_m and μ_l are the respective viscosities of the pulp and water in centipoises, ϕ_s is the volume fraction of the solids, and the coefficient c has a value of from 1 to 1,5. For these calculations, c was taken as 1 and ϕ_s was taken as 0,18. The results show the expected increase in viscosity with decrease in temperature.

The photographic studies showed that, at the higher viscosity, the rate at which the bubbles rose was lower and the number of bubbles per unit volume greater.

Discussion

As was expected from a consideration of the fundamentals of the flotation process, this study showed that temperature affects mainly the rate of pyrite flotation and has little effect on the final recoveries. It was also shown that, at temperatures below 10°C, a marked change occurs in the trend of decreasing rate constants for the flotation of pyrite. This change was highly reproducible, and occurred in the presence of a froth phase and in its absence. In the presence of a froth phase, the rate of flotation was slightly lower, probably because of the superimposed effect of the

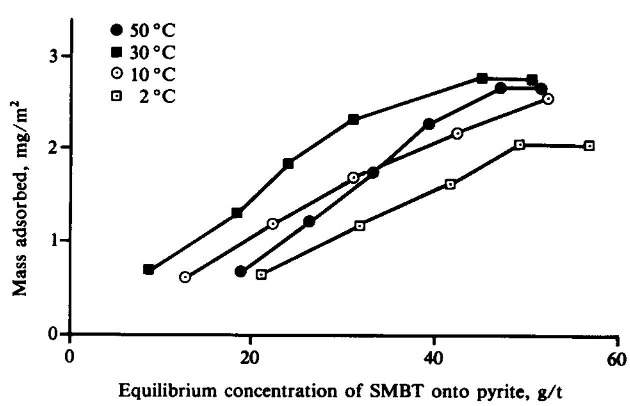

Fig. 7—Adsorption isotherms for sodium mercaptobenzothiazole (SMBT) onto pyrite

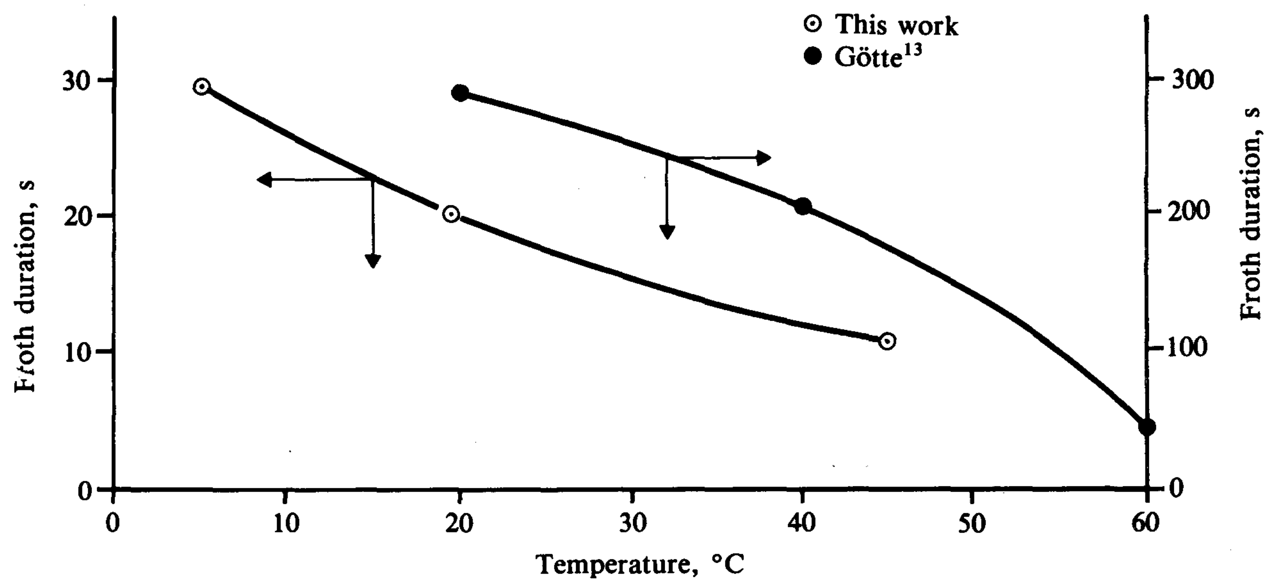

Fig. 8—Tests on froth stability

TABLE II
EFFECT OF COLLECTOR CONCENTRATION ON RECOVERY OF PYRITE AND GANGUE

SMBT concentration g/t	Pyrite ψ %	Pyrite $k \times 10^2 s^{-1}$	Gangue ψ %	Gangue $k \times 10^2 s^{-1}$
10	91,99	7,60	13,08	1,74
20	92,65	7,59	12,47	1,40
40	90,61	7,76	12,58	1,48
100	95,04	8,68	14,44	1,50
200	94,64	7,84	11,43	1,92

ψ = 'Infinite-time' recovery

TABLE III
EFFECT OF FROTHER CONCENTRATION ON RECOVERY OF PYRITE AND GANGUE

DOWFROTH 250 concentration g/t	Pyrite ψ %	Pyrite $k \times 10^2 s^{-1}$	Gangue ψ %	Gangue $k \times 10^2 s^{-1}$
—	85,12	7,91	7,01	1,41
10	87,37	7,96	10,26	1,65
20	89,66	7,72	12,67	1,38
40	88,55	8,02	15,72	1,72
80	88,66	8,80	17,75	1,68
160	91,20	8,33	21,64	1,50

ψ = 'Infinite-time' recovery

TABLE IV
EFFECT OF DEPRESSANT CONCENTRATION ON RECOVERY OF PYRITE AND GANGUE

ACROL (J2P350) concentration g/t	Pyrite ψ %	Pyrite $k \times 10^2 s^{-1}$	Gangue ψ %	Gangue $k \times 10^2 s^{-1}$
—	89,37	9,33	12,14	1,56
10	86,91	8,90	11,22	1,45
20	88,00	8,11	11,55	1,17
50	90,46	7,19	11,97	0,94
100	89,15	6,68	9,73	0,87

ψ = 'Infinite-time' recovery

TABLE V
EFFECT OF ACTIVATOR CONCENTRATION ON RECOVERY OF PYRITE AND GANGUE

$CuSO_4$ concentration g/t	Pyrite ψ %	Pyrite $k \times 10^2 s^{-1}$	Gangue ψ %	Gangue $k \times 10^2 s^{-1}$
—	89,37	9,33	12,14	1,56
20	88,61	9,19	12,67	1,51
50	90,25	8,52	12,9	1,26
100	89,32	8,39	11,30	1,43

ψ = 'Infinite-time' recovery

TABLE VI
EFFECT OF AERATION RATE ON RECOVERY OF PYRITE AND GANGUE

Aeration rate l/min	Pyrite ψ %	Pyrite $k \times 10^2 s^{-1}$	Gangue ψ %	Gangue $k \times 10^2 s^{-1}$
3	82,31	2,38	8,93	0,17
5	86,38	5,89	8,96	0,70
7	88,55	8,02	15,72	1,72
9	91,06	10,75	19,69	1,92

ψ = 'Infinite-time' recovery

TABLE VII
EFFECT OF IMPELLER SPEED ON RECOVERY OF PYRITE AND GANGUE

Impeller speed r/min	Pyrite ψ %	Pyrite $k \times 10^2 s^{-1}$	Gangue ψ %	Gangue $k \times 10^2 s^{-1}$
800	85,77	4,57	11,45	0,52
950	83,97	6,89	10,24	1,02
1100	88,11	5,97	11,04	0,68
1300	89,66	7,72	12,67	1,38
1450	89,11	8,94	11,90	1,49
1600	89,63	8,45	12,12	1,57

ψ = 'Infinite-time' recovery

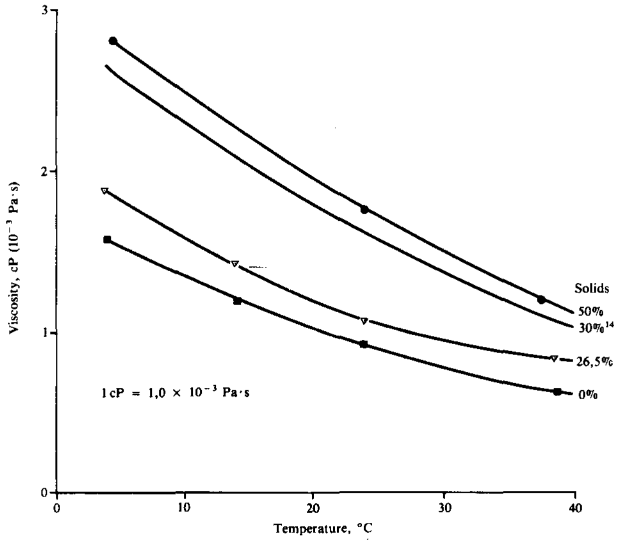

Fig. 9— Effect of temperature on pulp viscosity

lower velocity of the froth. A similar trend in the rates of flotation was observed by Klimpel[12] in the flotation of silica from a taconite ore.

Slightly less pyrite was recovered (92 per cent as compared with 98 per cent) when a froth phase was present, probably as a result of normal froth effects such as crowding and bubble breakage. Lowering of the pulp temperature decreased the rate of flotation since it decreased the velocity of the froth, increased the viscosity of the pulp, and reduced the rate of mass transfer of the pyrite from the pulp to the froth. The influence of temperature on the rate of pyrite flotation was virtually the same in the presence of a froth phase as it was in its absence (Figs. 3 and 5); so the most important of these factors is probably the rate of mass transfer of the pyrite from the pulp to the froth phase.

The reason for the decrease in the rate of mass transfer has not yet been identified, but this decrease may be due to one of the following factors:

(a) poorer loading of bubbles as the result of decreased induction time,
(b) lower rate of bubble rise, or
(c) fewer bubbles per unit volume of pulp.

Induction time, defined as the time necessary for the thinning of the bubble liquid layer to a critical thickness at which rupture occurs, is affected by several variables[15] such as the viscosity of the bulk liquid and the concentrations of the flotation reagents. Less collector is adsorbed at lower temperatures, but the rate of pyrite flotation is hardly affected by a change in collector concentration. Therefore, the extent of collector adsorption does not appear to be responsible for the marked change in the flotation rate. The other parameters that affect induction time have yet to be evaluated.

The rate of bubble rise was observed to be slower for colder pulps of higher viscosity. Although this is consistent with the observed lower rate of flotation at low temperatures, other factors, e.g. induction time, may be as important, or more important.

Photographic studies showed that, at low temperatures, there were more bubbles per unit volume than at high temperatures. This, and the fact that the flotation rate did not vary considerably with varying quantities of frother, do not sustain the hypothesis that the slower rate of flotation at low temperature is caused by the presence of fewer bubbles per unit volume.

At lower temperatures, flotation of the gangue is affected as follows. The rate of mass transfer from the pulp to the froth, the elutriation of gangue from the froth phase, and the velocity of the froth are lower, and the froth is more stable. At temperatures below 10°C, the k and ψ temperature profiles for gangue (Figs. 4 and 5) are markedly different from those for pyrite in the presence of a froth phase, in that the rate of gangue flotation increases. This phenomenon is ascribed to the effect of the increased stability of the froth and the viscosity of the elutriating medium, which cause less gangue to return to the pulp by bubble breakage or by elutriation. In the flotation of gangue at lower temperatures, these two effects appear to overshadow the effect of reduced froth velocity and of lower mass-transfer rates from the pulp to the froth. The different profiles obtained for the rate of gangue flotation in the presence of a froth phase and in its absence indicate that, with respect to the rate of gangue flotation, the effect on the froth phase at lower temperatures is most significant, resulting in greater recoveries of gangue and seriously reduced grades. This is shown clearly in Fig. 6.

It has been shown[16] that the rate of adsorption of SMBT onto pyrite decreases with temperature. Fig. 7 shows the effect of temperature on the equilibrium adsorption of SMBT. However, in all instances, a pseudo-equilibrium adsorption of collector, approximately equivalent to a double layer of reagent molecules, is obtained after 4 minutes. Monolayer coverage is obtained at all temperatures after less than 1 minute. The adsorption isotherms show that, at higher temperatures, desorption may occur. The equilibrium adsorption at 2°C is significantly lower than at ambient temperature, but is nevertheless adequate for flotation to occur. Hence, since adequate amounts of reagent are adsorbed within the normal conditioning time, viz 4 minutes, the rate of reagent adsorption is not considered to be rate controlling.

Conclusions

This study showed that the flotation rate of pyrite decreases with temperature owing to a reduction in the rate of mass transfer of pyrite from the pulp to the froth. This, in turn, is probably partly because the bubbles rise more slowly at lower temperatures, and hence higher viscosities. The effect of temperature on induction time was not investigated. It was also shown that the rate of gangue flotation is influenced mainly by the effect of temperature on the stability of the froth and the viscosity of the elutriating medium.

These effects of a decrease in temperature cannot be overcome by changes in reagent concentrations. As this study simulated the effect of temperature on the rougher banks of flotation plants, it is concluded that, for adequate grades to be maintained at lower temperatures, the load on the cleaner will have to be increased. An increase in aeration rate would improve the flotation rate and infinite-time recovery of pyrite. This alone does not offer a solution to the problem encountered during the winter months (Fig. 1), since there will be a similar increase in gangue flotation.

The use of higher impeller speeds results in improved flotation rates and recoveries of pyrite without a reduction in grade, and this may overcome the effects of decreased temperatures.

Finally, it is concluded that, although heating of the pulp may improve the recoveries, the economics must be carefully evaluated for each flotation plant. An example of such an evaluation is given in the addendum.

Acknowledgements

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Addendum

If a flotation plant with a feed rate of 19 000 t/d yields 500 t of concentrate and 3800 g of gold per day during winter and a 10°C rise in temperature will result in an increase of 7,5 per cent in the amount of concentrate produced, the gold recovery will be approximately 4085 g/d.

Thus,

the feed rate of pulp	=	19 000 t/d
the heat capacity of pulp	=	3,15 kJ/(kg.K), calculated on a weighted average at a pulp density of 30 per cent and a heat capacity of the solids of 0,7 kJ/(kg.K)
the enthalpy of the steam (100 kPa, 250°C)	=	2944 kJ/kg
the steam costs	=	R3,50 (including capital costs)
the gold price	=	R12 000 per kilogram.

Therefore, if the heat losses are 40 per cent, the cost of heating the pulp will be R1185 per day, and the increased revenue from gold will be R3420 per day.