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The recovery of copper and lead minerals from Tsumeb flotation tailings by magnetic separation

by J. SVOBODA*, R.N. GUEST†, and W.J.C. VENTER‡

SYNOPSIS

Wet high-intensity magnetic separation was examined as a method for the recovery of copper and lead from Tsumeb flotation tailings. Bench-scale and pilot-plant tests were conducted and, despite the very low magnetic susceptibilities of all the complex copper and lead minerals, copper and lead recoveries of over 60 per cent and almost 50 per cent respectively were obtained at a combined copper and lead grade of up to 13,5 per cent. The recoveries were found to be practically independent of magnetic induction in the range 0,5 to 2,2 T, and the grade of the magnetic concentrate decreased with increasing magnetic induction. The grade of the magnetic concentrate improved when the flowrate of the slurry was increased, and desliming was found to have a profound effect on the metallurgical process. Particles smaller than 10 μm were not recovered, and their presence in inefficiently deslimed samples impaired the overall performance of the magnetic separator.

SAMEVATTING

Nat magnetiese skeiding by 'n hoë intensiteit is ondersoek as 'n metode vir die herwinning van koper en lood uit die Tsumeb-flottasie-uitskot. Daar is bankskaal- en proefaanlegtoetse uitgevoer en ten spyte van die baie lae vatbaarheid van al die komplekse koper- en loodminerale, is koper- en loodherwinnings van onderskeidelik meer as 60 persent en byna 50 persent met 'n gekombineerde koper- en loodgraad van tot 13,5 persent verkry. Daar is gevind dat die herwinnings prakties afhang van magnetiese induksie in die strek 0,5 tot 2,2 T en die graad van die magnetiese konsentraat het afgeneem met toenemende magnetiese induksie. Die graad van die magnetiese konsentraat het verbeter met 'n verhoging van die vloeitempo van die flodder en daar is gevind dat ontslyking 'n groot uitwerking op die metallurgiese proses het. Partikels kleiner as 10 μm is nie herwin nie en hul aanwesigheid in monsters wat nie behoorlik ontslyk is nie, het die algehele werkverrigting van die magnetiese skeier benadeel.

Introduction

The Tsumeb Mine is situated in the north of South West Africa/Namibia. Of the total of 217 minerals accredited to the Tsumeb deposit, 41 have not been found elsewhere.

An oxidized zone is present from 884 m below surface down to the present working level of 1340 m, and the oxidized material from this zone has a deleterious effect on the metal recoveries from Tsumeb ore. The problem is addressed in this paper.

The current production of the mine is 53 kt of ore per month. The minerals that respond readily to flotation are tennantite, chalcocite, bornite, native copper, cuprite, malachite, galena, cerussite, and sphalerite, but poor recoveries are obtained from ore containing substantial amounts of conichalcite, mottramite, duftite, bayldonite, mimetite, and other complex copper and lead vanadates and arsenates.

The Council for Mineral Technology (Mintek) undertook to investigate the possibility of improving the recovery of copper and lead by magnetic- and gravity-separation techniques. The investigation consisted of batch and semi-continuous tests in the laboratory at Mintek and in a pilot plant at the mine. These are dealt with separately in the following sections.

Laboratory Tests

As the magnetic properties of the complex minerals in Tsumeb ore have never been investigated, it was imperative to measure the magnetic susceptibility of these minerals. The magnetic susceptibilities of samples collected at Tsumeb and purified at Mintek were measured by an a.c. induction bridge. The results are summarized in Table I and compared with values available in the literature[1].

Owing to the complications involved in obtaining pure minerals, to the fluctuations in the chemical composition of mineral compounds, and to the low magnetic susceptibilities, the agreement between the measured and the literature values is good. The possibilities for efficient magnetic separation, particularly of lead, are limited, owing to its very low magnetic susceptibility.

In order to investigate the amenability of flotation tailings from the Tsumeb plant to upgrading by magnetic separation, an experimental programme was undertaken in which the effect of the magnetic field, flowrate and density of the slurry, and desliming of the sample were investigated.

The experimental parameters used in the tests are summarized in Table II.

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* Specialist Scientist
† Group Leader, Ore-dressing Division
Both the above of the Council for Mineral Technology (Mintek), Private Bag X3015, Randburg, 2125 Transvaal.
‡ Manager: Mineral Production, Tsumeb Corporation Limited, P.O. Box 40, Tsumeb, 9000 Namibia.

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TABLE I
COMPARISON OF MAGNETIC SUSCEPTIBILITIES OF TSUMEB MINERALS MEASURED BY a.c. INDUCTION BRIDGE WITH VALUES FROM THE LITERATURE

Mineral	Chemical formula	Specific magnetic susceptibility (cm^3/g) × 10^{-6}	Literature[1] values (cm^3/g) × 10^{-6}
Azurite	$2\ CuCO_3Cu(OH)_2$	13,7	10,5
Descloizite	$PbZn(VO_4)OH$	0,4	
Bornite	Cu_5FeS_4	5,3	8,0
Tennantite	$5\ Cu_2S.2(Cu,Fe)S.2As_2S_3$	6,5	
Malachite	$CuCO_3.Cu(OH)_2$	6,8	8,5
Conichalcite	$CaCu(AsO_4)(OH)$	8,6	
Mimetite	$Pb_5(AsO_4)_3Cl$	−1,7	
Mottramite	$PbCu(VO_4)(OH)$	3,0	
Cerussite	$PbCO_3$	−1,9	−0,23
Duftite	$PbCu(AsO_4)(OH)$	4,2	

TABLE II
THE OPERATING CONDITIONS IN THE LABORATORY TESTS

Parameter	Eriez batch magnetic separator	Solenoid magnetic separator
Background magnetic induction, T	0,5 to 1,2	0,5 to 2,2
Interstitial velocity of the slurry in the matrix, cm/s	1,5 to 31,5	3,5 to 13,2
Matrix	Balls (6 mm) Mesh (wire diameter 1,6 mm, aperture 5 mm) Knitmesh (wire diameter 250 μm)	Balls (7 mm)
Matrix loading (mass of magnetics per matrix volume), g/cm^3	0,11 (ball matrix) 0,14 (mesh matrix)	0,06
Matrix height, mm	200	200

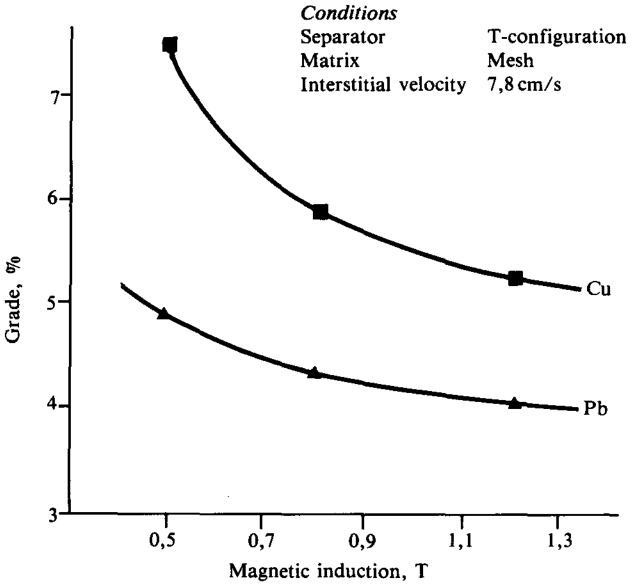


Fig. 1—Effect of magnetic induction on the grade of the magnetic fraction of deslimed oxide tailings (J771)

The tests were carried out in a batch Eriez matrix magnetic separator using the transverse (T-) configuration, in which the directions of magnetic induction and the slurry flow are perpendicular to each other (Fig. 1). A fixed volume of water mixed with varying amounts of ore, depending on the loading of the matrix, was fed from a funnel through the matrix. The flowrate was controlled by the size of the nozzle at the discharge end, and a constant matrix loading was employed for all the matrices used.

At a later stage, a limited number of tests were performed on a solenoid magnetic separator. The solenoid separator employs the longitudinal (L-) configuration, in which the directions of the field and the slurry flow are parallel (Fig. 1), and generates a background magnetic induction of up to 2,3 T.

The six samples listed in Table III were used in the tests.

Effect of Magnetic Field

The results show that an increase in magnetic induction caused a decrease in the grade of the magnetic concentrate (Fig. 2) as a result of the non-selective formation of clusters of magnetizable particles and entrainment

TABLE III
DESCRIPTION OF SAMPLES USED IN THE TESTS

No.	Description	Grade, %		Specific magnetic susceptibility (cm^3/g) × 10^{-6}	Size % passing 75 μm
		Cu	Pb		
J871 U/F	Oxide tailings underflow (deslimed at Mintek)	0,53	1,09	13,4	42,4
J871 O/F	Oxide tailings overflow from cyclone (deslimed at Mintek)	0,90	2,50	40,5	100
J872	Oxide tailings overflow from cyclone (deslimed at Tsumeb)	0,47	1,30	10,4	76,5
J873	Oxide tailings underflow from cyclone (deslimed at Tsumeb)	0,51	1,14	18,9	19,5
J770	Oxide tailings	0,52	1,02	13,8	55,6
J771	Oxide tailings underflow from cyclone (deslimed at Tsumeb)	0,72	0,98	15,0	20,6
J772	Feed to oxide flotation circuit	0,99	2,27	22,2	56,2

TABLE IV

EFFECT OF MAGNETIC INDUCTION ON MAGNETIC SEPARATION

T-configuration, matrix: mesh, interstitial velocity 7,8 cm/s

Magnetic induction T	Sample	Mass yield % into mags	Grade of mags %		Recovery into mags %		Calculated head %		Concentration ratio		Head %	
			Cu	Pb	Cu	Pb	Cu	Pb	Cu	Pb	Cu	Pb
0,5	J770	6,7	2,26	2,92	28,4	19,0	0,48	0,98	4,7	3,0	0,52	1,02
	J771	4,0	7,45	4,84	45,7	20,4	0,65	0,94	11,5	5,2	0,72	0,98
0,8	J770	10,8	1,79	2,54	39,7	28,5	0,48	0,98	3,7	2,6		
	J771	7,0	5,85	4,27	55,9	31,5	0,73	0,95	8,0	4,5		
	J871 U/F	7,4	4,40	6,12	56,6	42,6	0,58	1,06	7,6	5,8	0,53	1,09
	J871 O/F	10,3	1,12	2,99	12,5	12,5	0,92	2,44	1,2	1,2		
	J872	13,3	1,58	3,48	42,3	34,4	0,50	1,35	3,2	2,6	0,47	1,30
	J873	8,7	3,76	5,36	52,8	39,0	0,62	1,20	6,1	4,5	0,51	1,14
1,2	J770	12,7	1,66	2,40	43,7	31,2	0,48	0,98	3,5	2,5		
	J771	8,4	5,21	4,03	66,5	36,7	0,66	0,92	7,9	4,4		
	J871 U/F	9,8	3,48	5,43	63,2	46,4	0,54	1,15	6,4	4,7		
	J871 O/F	17,2	1,08	2,97	20,7	20,5	0,90	2,49	1,2	1,2		
	J872	11,6	1,73	3,73	41,5	32,6	0,48	1,33	3,6	2,8		
	J873	10,3	3,44	4,88	59,4	43,8	0,60	1,15	5,7	4,2		

TABLE V

EFFECT OF MAGNETIC INDUCTION ON MAGNETIC SEPARATION OF SAMPLE J771

L-configuration, matrix: 7 mm balls

Magnetic induction T	Flowrate cm/s	Mass yield, % into mags	Grade of mags %		Recovery into mags %		Concentration ratio	
			Cu	Pb	Cu	Pb	Cu	Pb
0,6	3,5	17,6	2,87	2,38	71,9	47,6	4,1	2,7
0,8		17,2	2,91	2,37	71,6	46,3	4,2	2,7
1,0		17,7	2,85	2,32	71,0	46,2	4,1	2,6
1,2		17,0	2,89	2,31	70,3	43,7	4,1	2,6
1,6		19,2	2,63	2,11	72,3	47,2	3,8	3,0
1,8		20,2	2,52	2,05	71,6	46,1	3,6	2,3
2,2		22,6	2,25	1,94	73,2	49,0	3,2	2,2
0,6	13,2	10,6	4,36	3,20	68,3	40,0	6,2	3,6
0,8		11,7	4,14	3,08	68,4	40,1	5,9	3,5
1,0		11,7	3,93	2,89	68,5	39,4	5,6	3,2
1,2		12,4	4,24	3,12	71,4	42,8	6,1	3,6
1,6		11,7	4,03	3,06	69,0	40,3	5,8	3,5
1,8		12,7	3,81	2,89	70,7	42,5	5,4	3,2
2,2		14,5	3,40	2,67	71,5	44,7	4,9	3,0

of the gangue. However, the recovery of copper and lead increased with a rise in the magnetic field up to 1,2 T in the T-configuration, as shown in Fig. 3. A solenoid magnetic separator was used to show the effect of the magnetic field at inductions higher than 1,2 T. The results are summarized in Figs. 4 and 5, and the mass balances of some selected tests are given in Tables IV and V.

In the L-configuration, the recovery of copper was practically independent of the field in the whole range studied (from 0,5 to 2,2 T), although a mild increase in the recovery of lead at high flowrates was observed. The recovery was substantially greater than that in the T-configuration, where it tended to increase with the magnetic field at low values of the field.

The grade of the magnetic fraction decreased mildly with the field in the L-configuration, indicating that high values of magnetic induction were detrimental to optimum metallurgical performance. With the T-configuration, the grade of the magnetic fraction was much higher than with the L-configuration. The difference in performance of a magnetic separator in the L- and T-configurations follows the pattern that can be expected from the theoretical description of magnetic separation. With the T-configuration, the build-up of particles on the sides of the balls is exposed to a large fluid shear, which reduces the recovery but improves the selectivity of the process by sweeping away the entrained particles of gangue as well as some less magnetic metal particles. With the L-configuration, as the build-up of particles on the upstream side of the balls is subject to a weaker shear stress, the recovery is higher at the expense of the grade of the concentrate. The geometrical configurations and

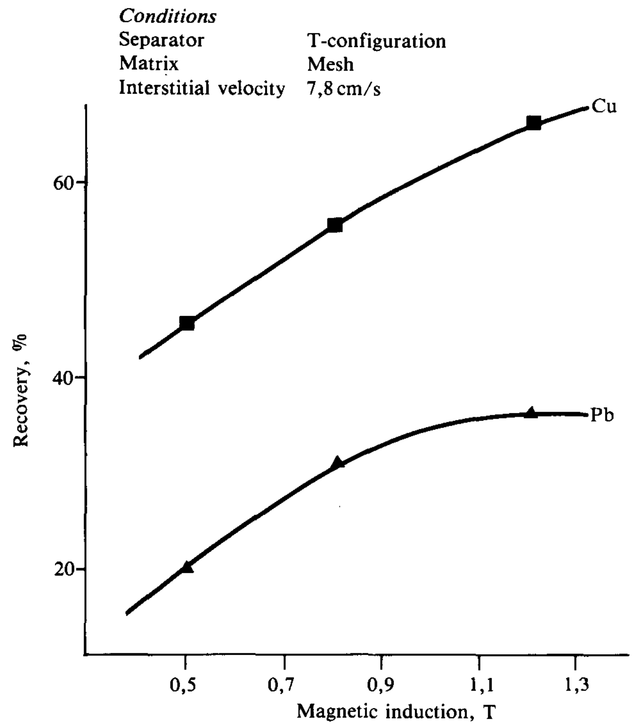


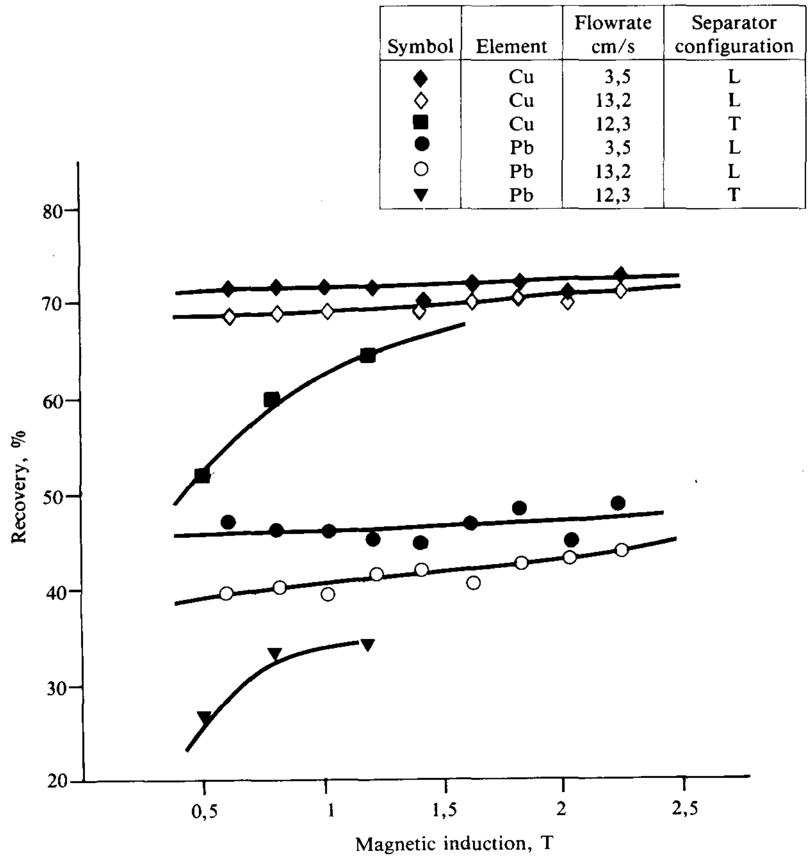
Fig. 2—Effect of magnetic induction on the recovery of copper and lead from deslimed oxide tailings (J771)

the build-up of particles in the matrix are illustrated schematically in Fig. 1.

Effect of Flowrate

The dependence of the recovery and grade of the magnetic concentrate on the flowrate is shown in Figs. 6 to 8 and in Table VI. Generally, as can be expected, the recovery decreased and the grade increased with increasing flowrate. However, for a properly deslimed sample (J871 U/F) at 1,2 T, the recovery was practically independent of the flowrate in the range studied, while the grade of the magnetic concentrate increased dramatically. At an interstitial velocity of 24 cm/s at 1,2 T and with a ball matrix, the recovery of copper amounted to almost 63 per cent and that of lead to about 38 per cent. The magnetic concentrate assayed over 6 per cent copper and 7,5 per cent lead. At an increased flowrate, the recovery would probably drop since the erosive force exerted by the fluid flow would overcome the attractive magnetic interaction between the matrix and the deposited mineral particles, as demonstrated by a drop in the recovery from sample J871 U/F at 0,8 T.

The lead minerals are less magnetic than the copper minerals, and consequently their sensitivity to the variations in flow velocity is greater. Even for a deslimed sample, the recovery of lead at 1,2 T dropped continuously with increasing flowrate.



Symbol	Element	Flowrate cm/s	Separator configuration
◆	Cu	3,5	L
◇	Cu	13,2	L
■	Cu	12,3	T
●	Pb	3,5	L
○	Pb	13,2	L
▼	Pb	12,3	T

Fig. 3—Effect of magnetic induction on the recovery of copper and lead from deslimed oxide tailings (J771) in a separator using 7 mm balls as the matrix

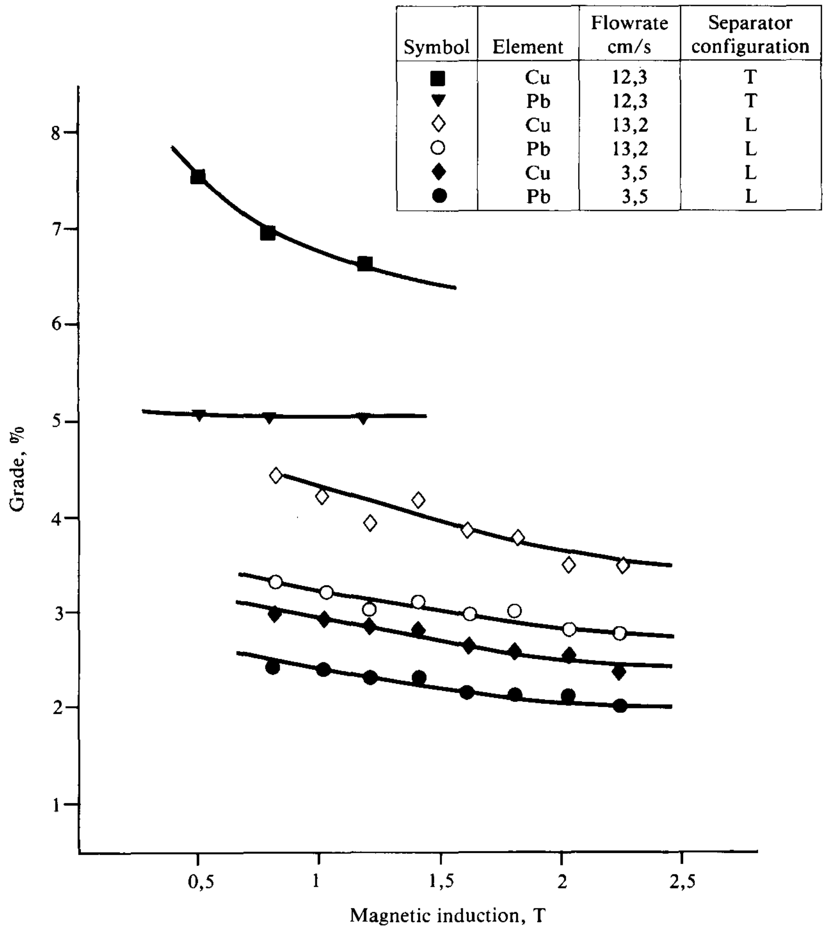


Fig. 4—Effect of magnetic induction on the grade of the magnetic concentrate of deslimed oxide tailings (J771) in a separator using 7 mm balls as the matrix

Comparison of Matrices

Although the comparative performance of the ball and mesh matrices were not studied systematically, some general trends can be deduced from the results.

The mesh matrix generally tended to give higher recoveries, while the ball matrix gave slightly higher concentrate grades. Similar behaviour had been observed in the upgrading of uranium–gold leach residues[2]. The Knitmesh matrix gave substandard results, the selectivity was very low, and even the recovery was markedly lower than that achieved with mesh and ball matrices. A comparison of the performance of various matrices is shown in Table VII.

The smaller the mean particle size of the feed, the more efficient was the performance of the mesh matrix compared with that of the ball matrix, especially for the very fine overflow fraction of sample J871, from which the mesh matrix recovered several times more copper and lead than the ball matrix.

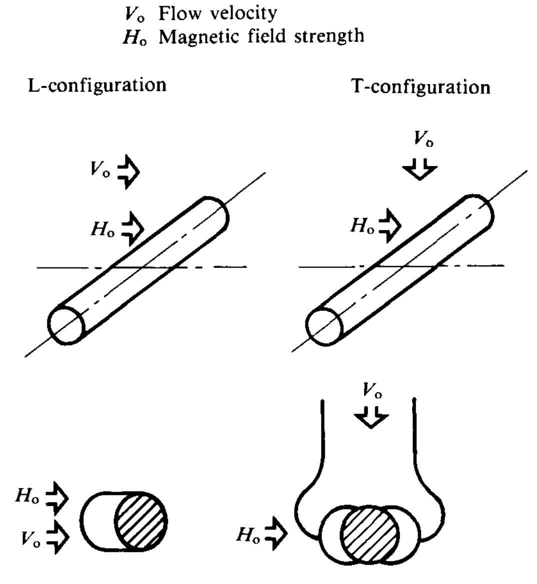


Fig. 5—Schematic representation of the geometrical configurations and the build-up of particles on the matrix

Magnetic Susceptibility

The magnetic susceptibilities of the products of the magnetic separation were monitored. It was observed that these values of the magnetic fraction decreased with increasing magnetic induction and decreasing flowrate, as a consequence of decreasing selectivity and increasing entrainment of diamagnetic gangue in the magnetic fraction.

The magnetic susceptibility of the non-magnetic fraction was, in most cases, negative (about -1×10^{-6} cm^3/g), indicating that all the paramagnetic minerals were recovered into the magnetic fraction. Nevertheless, it was still possible to recover the additional copper and lead by the use of an increased magnetic field or reduced flowrate. However, the use of magnetic fields higher than 1,2 T cannot be expected to lead to a substantial improvement in recovery.

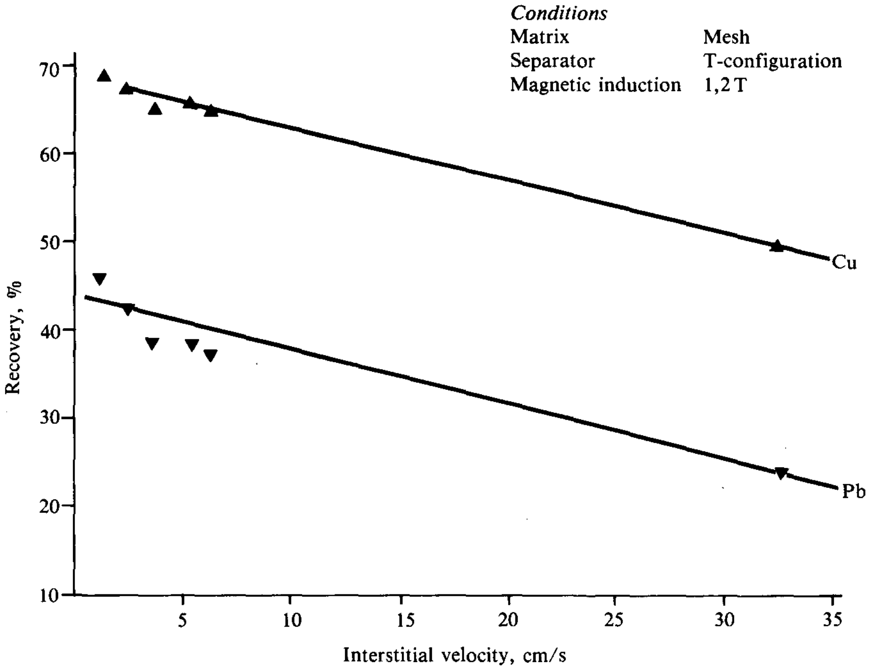


Fig. 6—Recovery of copper and lead from deslimed oxide tailings (J771) as a function of interstitial velocity

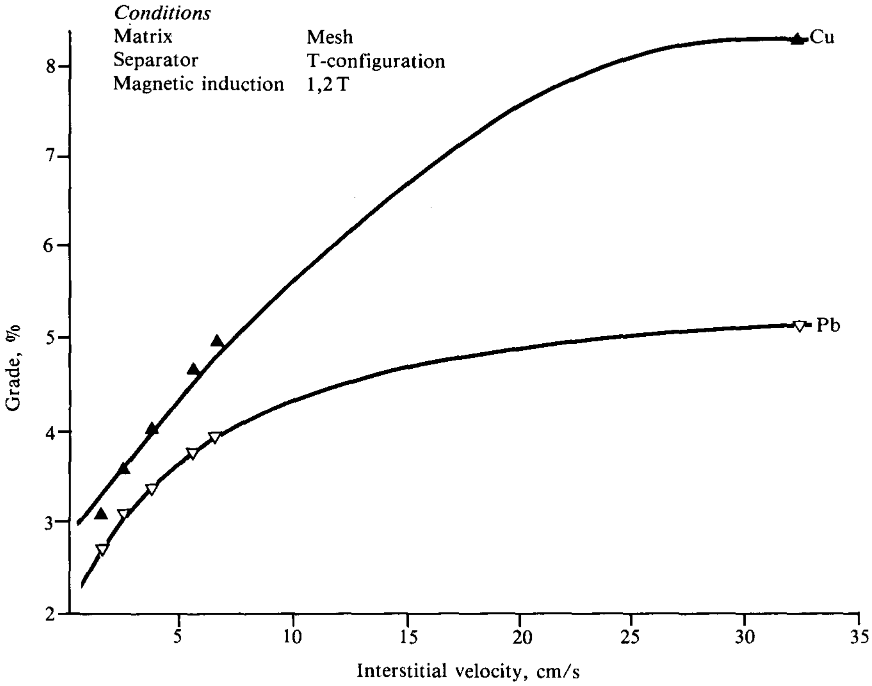


Fig. 7—Grade of magnetic concentrate of deslimed oxide tailings (J771) as a function of interstitial velocity

Malachite and mottramite reported to the magnetic fraction, as confirmed by the mineralogical analyses of the magnetic and non-magnetic fractions. Duftite and conichalcite, which were expected to report to the magnetic fraction, were surprisingly absent, while diamagnetic cerussite showed little preference for the magnetic or the non-magnetic fraction.

Effect of Desliming

Fines in the ore affected the metallurgical performance of the magnetic separator (Tables IV and VI). For deslimed samples, the recovery of copper was almost independent of the flowrate, while the grade of the concentrate increased dramatically with increasing slurry velocity. Therefore, at high flowrates, high recoveries could be obtained (well over 60 per cent copper and almost 50 per cent lead) at a high grade, i.e. a combined grade of copper and lead of 13,5 per cent. A high flowrate also results in the attainment of high throughputs.

Samples with a high content of material smaller than 10 μm (e.g. the fine overflow fraction J871 O/F) yielded very low recoveries, indicating that the efficiency of the magnetic separator had been severely impaired. However, the fines larger than 10 μm responded readily to magnetic separation. Therefore, desliming at about 10 μm would result in high recoveries at high grades and, as an additional advantage, only a small fraction of copper and lead would be lost in the slimes. Insufficient desliming at, say,

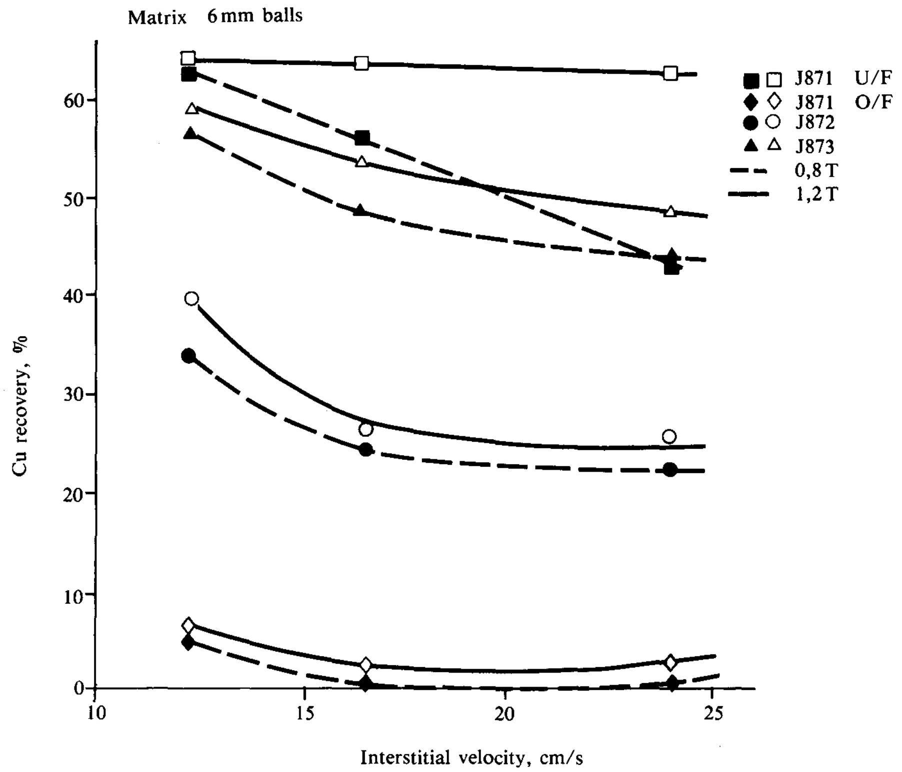


Fig. 8—Recovery of copper versus interstitial velocity

TABLE VI

EFFECT OF FLOWRATE ON MAGNETIC SEPARATION AT A MAGNETIC INDUCTION OF 1,2 T

T-configuration, matrix: 6 mm balls

Interstitial velocity cm/s	Sample	Mass yield % into mags	Grade of mags %		Recovery into mags %		Calculated head %		Concentration ratio	
			Cu	Pb	Cu	Pb	Cu	Pb	Cu	Pb
12,3	J871 U/F	8,4	4,24	6,05	63,9	45,7	0,56	1,11	7,76	5,5
	J871 O/F	1,9	3,14	5,54	6,7	4,2	0,89	2,50	3,5	2,2
	J872	8,4	2,26	4,09	40,1	25,6	0,47	1,34	4,8	3,1
	J873	9,5	3,77	5,11	59,4	41,7	0,60	1,16	6,3	4,4
16,5	J871 U/F	10,4	3,51	5,13	63,9	43,3	0,57	1,23	6,2	4,2
	J871 O/F	0,9	2,81	5,28	2,9	1,9	0,88	2,52	3,2	2,1
	J872	3,8	3,27	5,40	25,4	16,2	0,49	1,26	6,7	4,3
	J873	7,1	4,20	6,15	53,4	41,6	0,56	1,05	7,5	5,9
24,0	J871 U/F	5,3	6,03	7,48	62,8	38,1	0,51	1,04	11,8	7,2
	J872 O/F	1,0	2,97	5,12	3,2	2,1	0,92	2,49	3,2	2,1
	J872	3,3	3,50	5,64	27,2	14,1	0,42	1,32	8,3	4,3
	J823	5,4	5,46	6,83	48,6	33,0	0,60	1,12	9,1	6,1

20 μm would not significantly improve the efficiency of the magnetic separation.

Another interesting feature can be deduced from Tables IV and VI. At low flowrates, the mass yield into the magnetic fraction from the slimes (J871 O/F) far exceeded that from the deslimed samples, although the opposite would be expected in view of the fineness of the slimes. However, at high flowrates, the mass yield from the slimes dropped to a very low value, which supports the notion that the efficiency of capture in magnetic separation is determined primarily by the interplay between the static magnetic interaction of deposited particles with the matrix on the one hand, and the shear stress exerted on the particles by the fluid flow on the other.

The effect of particle size on the recovery and the concentration ratio are shown in Figs. 9 and 10 respectively. Proper desliming at 10 μm led to very high recoveries and concentration ratios, while inefficient desliming at a higher cut-off point reduced both the recovery and the concentration ratio. A coarser slime fraction still contained minerals that are susceptible to magnetic upgrading. On the other hand, for sample J873, which contained particles larger than 100 μm, the recovery was affected by the increasing role of the gravitational force.

Discussion

Despite the very low magnetic susceptibilities of the minerals present in Tsumeb flotation tailings, it was pos-

TABLE VII

COMPARISON OF THE PERFORMANCE OF VARIOUS MATRICES AT A MAGNETIC INDUCTION OF 1,2 T

Sample J771

Matrix	Flowrate	Mass yield into mags %	Grade of mags %		Recovery into mags %		Concentration ratio	
			Cu	Pb	Cu	Pb	Cu	Pb
Mesh	7,8	8,4	5,21	4,03	66,5	36,7	7,9	4,4
	2,6	13,0	3,59	3,12	67,3	42,5	5,4	3,4
6 mm balls	12,3	6,4	6,78	5,06	64,6	33,4	10,0	5,3
	2,6	12,2	3,89	3,62	68,3	45,3	5,6	3,7
Knitmesh	6,4	10,2	3,38	2,83	52,3	30,1	5,3	3,0
	3,3	11,7	2,59	2,24	51,4	31,4	4,2	2,5

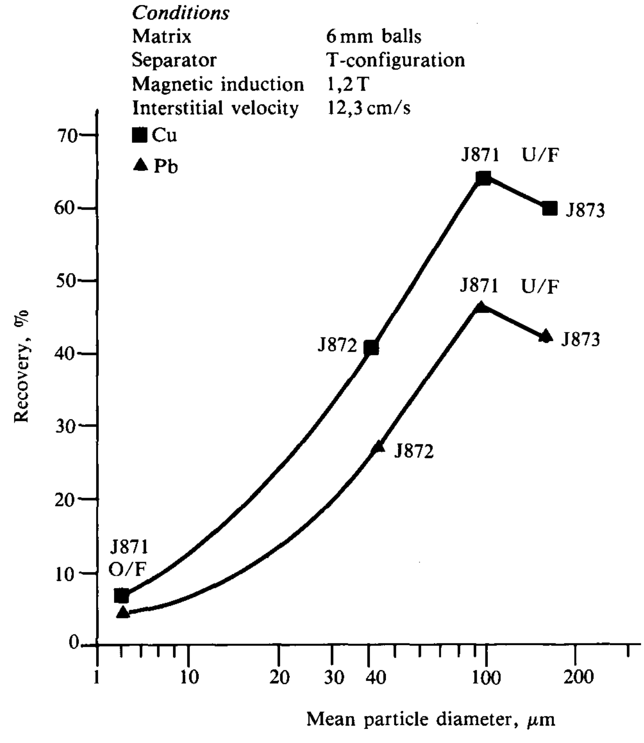


Fig. 9—Effect of mean particle size on recovery

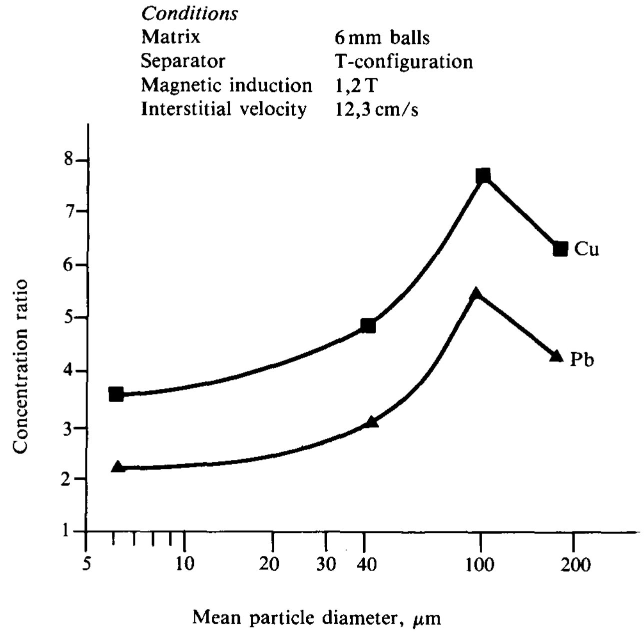


Fig. 10—Effect of mean particle size on the concentration ratio

sible to recover up to 70 per cent of the copper and 50 per cent of the lead into the magnetic concentrate. Table I shows that the copper can be expected to respond more readily to magnetic separation than the lead, because some of the copper compounds are weakly paramagnetic while some of the lead minerals are diamagnetic. This was confirmed by the experimental results. The fact that the magnetic susceptibility of the non-magnetic fraction was negative in most cases indicates that the magnetic separation recovered all the paramagnetic components from the tailings, and that no further improvement in recovery can be expected.

With the separator in the T-configuration and with low magnetic fields, the recovery of copper and lead increased with increasing field until the maximum was reached at around 1,2 T. With the separator in the L-configuration, the recovery was higher and did not depend on the field strength used in the range investigated (from 0,5 T to 2,2 T). However, the selectivity of the magnetic separation was much better in the T-configuration, and decreased with increasing magnetic field.

The grade of the magnetic concentrate can be improved by the use of an increased slurry flowrate through the matrix. For deslimed samples, the recovery was practically independent of the flowrate, but the grade of the magnetic fraction increased dramatically as the flowrate increased.

The recovery was found to be independent of the pulp density in the range investigated (3 to 17 per cent solids). The grade of the magnetic fraction initially rose sharply with increasing density up to 5 per cent solids, but remained constant above that value.

The performance of the ball and mesh matrices was similar, although the mesh matrix was superior for very fine material. The fine Knitmesh matrix was very nonselective and the recoveries were unacceptable. This observation again emphasizes the importance of experimental optimization of the conditions of separation, and the negative role that some theoretical models of magnetic separation may play in process optimization.

The recoveries of copper and lead were not dependent on the pH of the slurry. This was contrary to expectations in that, for very fine particles, the surface forces between the particles had been expected to play a significant role in the separation process. However, the grade of the magnetic fraction depended very strongly on pH, the maximum grade being obtained at a pH value of 1,5 and the minimum at a pH value of 8, close to the pH of the slurry in the plant. The improvement in the grade when the pH value was adjusted from 9 to 1,5 amounted to about 45 per cent for copper and 35 per cent for lead. The role of the surface forces cannot be quantitatively analysed since the surface properties, particularly the zeta potentials of the complex compounds present in the tailings, are unknown.

Desliming was found to have a profound effect on the metallurgical response of the samples. Particles smaller than 10 μm were not recovered, and their presence in samples that had not been properly deslimed impaired the overall performance of the magnetic separator.

Inefficient desliming increased the losses of metal to the fines of material that could be amenable to recovery by magnetic separation.

Two-stage magnetic separation led to an improvement in the grade of the magnetic fraction (up to 16 per cent combined copper plus lead), but the recovery was reduced. The same results can be obtained by single-stage wet high-intensity magnetic separation (WHIMS) at high flowrates.

It was observed that, besides copper and lead, other elements in the flotation tailings could be recovered by WHIMS. The results are summarized in Table VIII, which shows that zinc followed a similar pattern to that of lead, and that recoveries of about 40 per cent into the magnetic fraction were obtained.

Arsenic responds very well to magnetic separation, and a recovery of up to 80 per cent at a concentration ratio of 8 was obtained. This was expected since the arsenic-containing minerals have positive magnetic susceptibilities.

Silver, which is associated mainly with the sulphide minerals, is recovered by WHIMS to a lesser degree. A recovery of more than 20 per cent at a concentration ratio of 2 was recorded.

Pilot-plant Tests

The laboratory testwork was followed by tests on a pilot plant that was set up at the Tsumeb concentrator. An Eriez CF-30 carousel magnetic separator was used, which has a nominal capacity of 1,5 t/h, generates a background magnetic field of 0,8 T, and is filled with a matrix of 6 mm steel balls. The ball charge was continuously removed from the carousel for cleaning[3]. The magnetic and non-magnetic fractions were collected and analysed. The middlings reported to four compartments, the middlings from the two compartments closest to the magnetic launder being pumped to the magnetic fraction. This combined product was called the 'concentrate'. The middlings from the other two compartments were pumped to the non-magnetic fraction, and this combined product was called the 'tailings'.

The aim of the tests was to show the effect of the following variables: pulp density, feed rate, volume of rinsing and flushing water, and influence of a dispersant. The variations in these parameters are summarized in Table IX, and the results for selected tests are shown in Table X.

Direct interpretation of the experimental results is not easy because fluctuations in the process caused unsteady flow conditions, which had a negative effect on the reproducibility of the results.

Pulp Density

The effect of the pulp density on the grade and recovery was not pronounced. The grade of the magnetic fraction was higher than that of the concentrate (magnetic fraction plus two middlings), and the recovery of copper and lead into the concentrate improved when the middlings from at least two boxes were combined with the magnetic fraction. This was justified because of the small differences in the grades of the products.

TABLE VIII

RECOVERY OF ZINC, ARSENIC, AND SILVER FROM TSUMEB FLOTATION TAILINGS BY WHIMS

T-configuration, matrix: 6 mm balls, flow velocity: 12,3 cm/s

Test no.	Sample	Magnetic induction T	Mass yield into mags %	Grade of mags, %					Recovery into mags, %				
				Cu	Pb	Zn	As	Ag*	Cu	Pb	Zn	As	Ag
1	J871	1,2	8,9	4,07	5,49	1,93	3,29	37	56,7	47,3	32,2	73,8	18,4
2	J873	1,2	10,3	4,06	5,60	2,00	3,84	42	62,7	56,1	39,7	79,5	21,2
3	J871 2nd pass of mags from test 1	0,8	38,9	6,16	7,38	2,34	4,89	57	65,6	59,2	48,8	94,1	61,3
4	J873 2nd pass of mags from test 2	0,8	57,8	6,01	7,99	2,38	5,74	49	85,7	81,0	68,8	98,3	77,0

* p.p.m.

TABLE IX
VARIATION IN THE PARAMETERS OF THE MAGNETIC-SEPARATION TESTS IN THE PILOT PLANT

Parameter	Range
Solids content of pulp	19 to 44 per cent
Feed rate	0,99 to 1,46 t/h
Rinsing water	10 to 20 l/min (0,6 and 1,2 m^3/t)
Flushing water	30 to 70 l/min (1,8 to 4,2 m^3/t)
Matrix loading	0,08 to 0,11 g/cm^3

Feed Rate

Within the range of feed rates investigated, there was practically no variation in the performance of the separator, although an optimum feed rate of 1,1 t/h was indicated.

Rinsing and Flushing Water

The grades of the magnetic fraction and of the concentrate almost doubled and the recovery decreased when the flow of rinsing water was increased from 10 to 20 l/min. The flowrate of the flushing water had no effect, and the only requirement in regard to the volume involved was to keep the matrix clean for a sufficiently long time.

Desliming

Desliming as performed in the plant did not affect the operation of the magnetic separator, whereas desliming was beneficial to the performance of a WHIMS machine when it was used in the beneficiation of uranium-gold leach residues from the Witwatersrand. The plant tests on the sample that had not been deslimed gave surprisingly better results than those obtained in the laboratory. The grade was higher for a continuous machine, while the recovery scarcely changed.

The results of the laboratory and pilot-plant tests on a deslimed pulp were markedly different, the grades and the recoveries obtained in the laboratory tests being substantially better. This can be explained only if it is assumed that the desliming circuit of the plant was operating inefficiently.

The grade of the non-magnetic fractions in the laboratory and pilot-plant machines were almost the same. The carousel machine therefore worked with a high degree of efficiency, and the reason for unsatisfactory metallurgical results should be sought in the preparation of the feed pulp and, possibly, in the adjustment of the rinsing water.

Dispersant

The presence of a dispersant (sodium silicate) was found to double the grade of the magnetic fraction and, surprisingly, there was also a slight improvement in the recovery of copper.

Conclusion

Despite the very low magnetic susceptibilities of the minerals present in the Tsumeb flotation tailings, it was possible to recover up to 70 per cent of the copper and 50 per cent of the lead into the magnetic concentrate at a combined grade of less than 15 per cent copper and lead.

With the separator in the T-configuration, the recovery of copper and lead increased with increasing magnetic field until the maximum was reached at 1,2 T. In the L-configuration, the recovery was independent of the magnetic field in the range 0,5 to 2,2 T.

The recovery was higher in the L-configuration than in the T-configuration, while the grade of the magnetic concentrate was lower. The selectivity of separation decreased with increasing magnetic field and could be improved by the use of a higher slurry flow velocity. Relatively coarse matrices (balls and mesh) gave superior results, although the mesh matrix was found to be more efficient for fine material. Particles smaller than 10 μm were not recovered, and desliming substantially improved the metallurgical performance of the magnetic separator. In the pilot-plant operation, the variations in pulp density, feed rate, and flushing-water volume did not affect the operation of the separator, while the flowrate of rinsing water was found to be critical.

Since the quality of the magnetic concentrate could not be improved sufficiently by magnetic separation alone, gravity separation in the form of a shaking table was used for further upgrading. This cleaning operation reduced the recoveries of copper and lead to the same level as those obtained by an all-gravity circuit[4].

References

1. Andres, U. Magnetohydrodynamic and magnetohydrostatic methods of mineral separation. New York, J. Wiley and Sons, 1976.

TABLE X
RESULTS OF SELECTED PILOT-PLANT TESTS
Matrix: 6 mm balls, magnetic induction: 0,8 T, interstitial velocity: 10 cm/s

			Cu				Pb			
Sample	Solids %	Feed rate t/h	Grade of mags %	Grade of conct. %	Recovery into mags %	Recovery into conct. %	Grade of mags %	Grade of conct. %	Recovery into mags %	Recovery into conct. %
Not deslimed	33	0,9	2,8	2,7	38,0	38,6	3,1	2,7	–	26,2
	29	0,9	3,5	3,2	32,9	43,9	4,6	4,3	20,7	37,7
Deslimed	35	0,95	2,6	2,0	44,5	33,8	2,6	2,3	26,0	22,7
	42	1,5	3,3	3,7	42,4	52,5	3,7	3,6	31,6	37,0
Dispersant	23	0,44	2,2	2,0	64,7	68,7	2,5	2,3	46,7	50,2
	32	0,85	1,4	1,1	62,6	60,7	1,3	1,1	51,4	53,6