The behaviour of minerals in sulphide flotation processes, with reference to simulation and control.

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SYNOPSIS

In sulphide flotation processes, there are two mechanisms by which particles are transferred from the flotation pulp to the concentrate: adhesion to air bubbles and natural flotation, and entrainment in the froth. The entrainment mechanism is particularly important for particles of non-sulphide gangue, which do not absorb collector. The importance of controlling the recovery rate of water was illustrated in plant testwork in which selectivity between valuable sulphides and sulphide gangue, and between valuable sulphides and non-sulphide gangue, was altered by manipulation of variables affecting the water recovery rate.

The two mechanisms should be recognized in the development of a control system. Most of the control schemes in operating plants have concentrated on reagent additions, which affect the natural flotation mechanism. Although control of the chemical environment is clearly of paramount importance in flotation, plant tests have shown that control of the variables affecting the entrainment mechanism is also important.

SAMEVATTING

In die sulfiedflottasieprosesse is daar twee meganismes waardeur partikels uit die flottasiepulp na die konsentraat oorgedra word: adhesie aan lugborrels en natuurlike flottasie, en saamsleping in die skuim. Die saamsleepmeganisme is van besondere belang vir partikels van nie-sulfiedaarsteen wat nie die versamelaar adsorbeer nie. Die belangrikheid van beheer oor die herwinningstempo van die water is geïllustreer in aanlegtoetswerk waar die selektiwiteit tussen waardevolle sulfiede en sulfiedaarsteen en tussen waardevolle sulfiede en nie-sulfiedaarsteen gewysig is deur die manipulasie van die veranderlikes wat die waterherwinningstempo beïnvloed.

Die twee meganismes moet in die ontwikkeling van 'n kontrolestelsel erken word. Die meeste kontrolestelsels in bedryfsaanlegginge het hulle toegespits op die byvoeging van reagense wat die natuurlike flottasiemeganisme beïnvloed. Hoewel beheer oor die chemiese omgewing vanselfsprekend van die allergrootste belang in flottasie is, het die aanlegtoetse getoon dat beheer oor die veranderlikes wat die meesleepmeganisme beïnvloed, ook belangrik is.

INTRODUCTION

In the concentration of mineral sulphides by flotation, advantage is taken of differences in the surface nature of the mineral species to separate the collector-coated valuable sulphides from the more hydrophilic sulphide and non-sulphide gangues. The metallurgical efficiency is governed by the ability of the process to produce sufficient difference in the recovery rates of the minerals to obtain a high recovery of the valuable sulphide at an acceptable grade. Selectivity is altered by a change in the operating variables, e.g., reagent additions, pulp level, air addition.

In recent years, there has been a movement in industry towards automatic control, the incentive being higher metallurgical efficiency. This improved efficiency stems from greater circuit stability and reagent savings, and from closer operation to the process limits. Many attempts

have been made to describe the processes mathematically so that computer simulation techniques can be used to develop circuit optimization and control procedures. Types of model have been described by Woodburn[1] and Jowett et al.[2]. The importance of the recovery rate of water on the process has not generally been recognized in simulation models, and this has resulted in poor agreement between the observed and predicted plant performance.

In the development of the models, much emphasis has been placed on theoretical and laboratory work, but little systematic data collection has been done in operating plants. Consequently, some of the complexities in the flotation process, such as the effect of entrainment, which may exert marked influences on the results of the process, have not been recognized. In this regard, it is pertinent to repeat the comments of Woodburn[1], that 'the formulation of [flotation] models can only be improved if a clear understanding of the role that the model is destined to

fulfil is possessed by the modeller', and that 'this normally requires a close interaction between operational practice and modelling theory'.

In research work on flotation modelling at the Julius Kruttschnitt Mineral Research Centre (JKMRC), the differential flotation rates of valuable sulphides and gangue minerals in sulphide ores have been investigated. Testwork has been conducted in several concentrators treating a variety of copper and lead-zinc sulphide ores. The plant work has been supplemented where necessary with particular laboratory and pilot-scale tests. The data obtained, together with such other plant data as are available, have been used in an investigation of the pattern of behaviour of the valuables and gangue minerals with a view to developing simulation and control techniques. These patterns of behaviour, as observed in operating plants and as affected by changes in some variables with control possibilities, are discussed in this paper.

Bubble attachment to the collector-coated sulphide surface has

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TABLE I
DESCRIPTION OF SULPHIDE ORES THAT WERE EXAMINED BY THE JKMRC

Company	Location	Main sulphide minerals	Gangue sulphide	Other gangue minerals	Reference
Philex Mining Corporation .	Luzon, Phillipines	Chalcopyrite (0,5% Cu)	Negligible	Quartz 93% Magnetite 6%	Johnson[10]
Mount Isa Mines Limited .	Queensland, Australia	Chalcopyrite (3,0% Cu)	Pyrite Pyrrhotite 6%	Quartz 75% Dolomite 10%	McKee[11]
Mount Lyell Mining and Railway Company Limited	Tasmania, Australia	Chalcopyrite (1,0% Cu)	Pyrite 10%	Quartz 87%	McKee[11]
Peko Mines Limited	Northern Territory, Australia	Chalcopyrite (3,0% Cu)	Pyrite 11%	Magnetite 50% Quartz $\}$ 30% Chlorite	Johnson[10]
Bougainville Copper Pty Limited	Bougainville Island, P.N.G.	Chalcopyrite (0,7% Cu)	Negligible	Quartz 95% Magnetite 3%	Johnson[10]
New Broken Hill Consolidated Limited . . .	N.S.W., Australia	Galena, Marmatite (8% Pb 13% Zn)	Negligible	Quartz Rhodonite	Thorne[12]
North Broken Hill Limited	N.S.W., Australia	Galena, Marmatite (13% Pb, 10% Zn)	Negligible	Quartz, Calcite Rhodonite	Thorne[12]

TABLE II
SOURCES OF OTHER PUBLISHED DATA ON SULPHIDE ORES

Company	Location	Main minerals	Reference
Nchanga Consolidated Copper Mines Limited .	Zambia	Chalcopyrite, malachite, quartz, silicates	Kelsall[13]
Mount Isa Mines Limited	Queensland, Australia	Chalcopyrite, pyrite, quartz, dolomite	Bull[14]
The Zinc Corporation Limited	N.S.W., Australia	Galena, marmatite	Bull[14]

long been recognized as the principal mechanism for the recovery of mineral sulphides by flotation. Considerable research (for example, Gaudin[3], Glembotskii et al.[4], Bull[5], Woodcock and Jones[6, 7]) has been done on the importance of variables that affect this mechanism. The entrainment mechanism, in which pulp is entrained between bubble-mineral aggregates and carried over into the concentrate launder, was discussed by Jowett[8] in 1966, and it has been shown in more recent work both in the laboratory and in continuous plants (Johnson et al.[9]) to be responsible for the recovery of free non-sulphide gangue. This mechanism is more selective with regard to particle size and specific gravity, but air bubble attachment is more selective with regard to mineral type since this determines the extent to which the particle surface can be made hydrophobic.

In this paper, the observed flotation behaviour of the mineral types is described, and an explanation for the behaviour is given in terms of flotation mechanisms. Sim-

ulation models are also discussed. Various flotation control schemes are discussed with reference to the observed mechanisms.

The sulphide ores studied in the JKMRC test programme are listed in Table I.

The sources of other published plant data on sulphide flotation processes are given in Table II.

SUMMARY OF THE FLOTATION BEHAVIOUR OF SULPHIDE ORES IN PLANT CIRCUITS

The recovery-time relationships for sulphide minerals, non-sulphide gangue, and water are shown in Fig. 1 for many of the rougher/scavenger banks discussed in this paper. The high flowrates of concentrate encountered in plant sampling usually make direct measurement of flowrates impracticable. Consequently, the recoveries of the components were based on the flowrates calculated by the two-product formula applied to assays and pulp densities.

The various minerals in the differ-

ent ores showed a common pattern of behaviour. The behaviour of the three main groups (i.e., sulphide valuable, sulphide gangue, and non-sulphide gangue) is discussed in more detail in the next section. The recovery-time curves for each size fraction of minerals in the Mount Isa rougher bank are shown in Fig. 2, and the consistency of behaviour from size to size will be noted. From the data available on industrial sulphide flotation processes, the following comments are made.

(1) For each ore, there is a significant difference between the rates of flotation of the valuable sulphides, gangue sulphides, and non-sulphide gangue.

(2) For each there is a similarity between the recovery rates of non-sulphide gangue and water.

(3) Even with the sulphide minerals, there is a dependence of recovery rate on the recovery rate of water.

FLOTATION RATES AND RECOVERY MECHANISMS
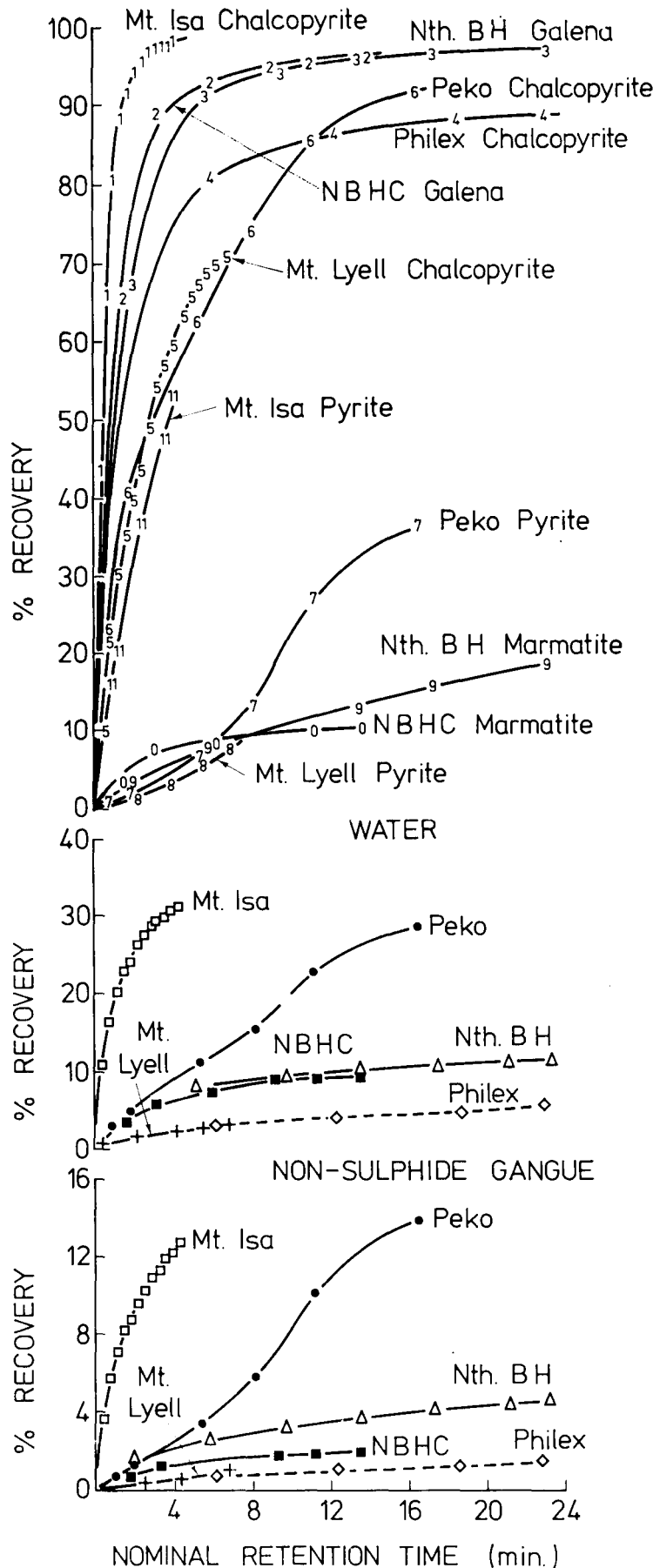
The recovery of a particular

Fig. 1—Behaviour of sulphide and gangue minerals and water in several chalcopyrite and galena flotation processes

mineral is the combined result of the selective bubble-attachment and water-entrainment recovery mechanisms. The relative importance of either mechanism depends on the nature of the mineral (e.g., type, fineness of grind), the chemical flotation environment (e.g., collector, modifier, salt concentrations), and the physical variables that affect the availability of air in the pulp and the recovery rate of water (e.g., frother, air, pulp level). This is illustrated, for example, in the lead flotation circuit of New Broken Hill Consolidated Limited (NBHC). Galena is selectively floated free of marmatite and non-sulphide gangue. The recovery-size curves after six rougher machines are shown in Fig. 3.

For galena, because the mineral has a high specific gravity and because most of the particles have a hydrophobic surface, selective attachment is more important. The shape of the curve is typical for valuable sulphides (Kelsall and Stewart[15], Morris[16]). Maximum recovery is obtained in an intermediate size range between about 15 and 70 μm, with lower recovery in the finer and coarser fractions. For marmatite, which is a less dense sulphide than galena and activated to only a minor extent, entrainment has a greater effect. In Fig. 3, the shape of the curve describing the recovery of the coarser sizes is characteristic of selective attachment, whereas the increase in recovery in the fines is evidence of entrainment. For the non-sulphide gangue, entrainment is still more important, except for the small percentage in composites with floatable sulphide.

A quantitative relationship has been developed between the recovery rates of water and free non-sulphide gangue, and this will be discussed later. These equations can be extended to describe the influence of the water recovery rate on the recovery rate of the sulphides.

FLOTATION MODELS

Non-sulphide Gangue

Some non-sulphide particles adsorb sufficient collector to make them hydrophobic, and they float by bubble attachment. However, the majority of non-sulphide particles do not become hydrophobic, and
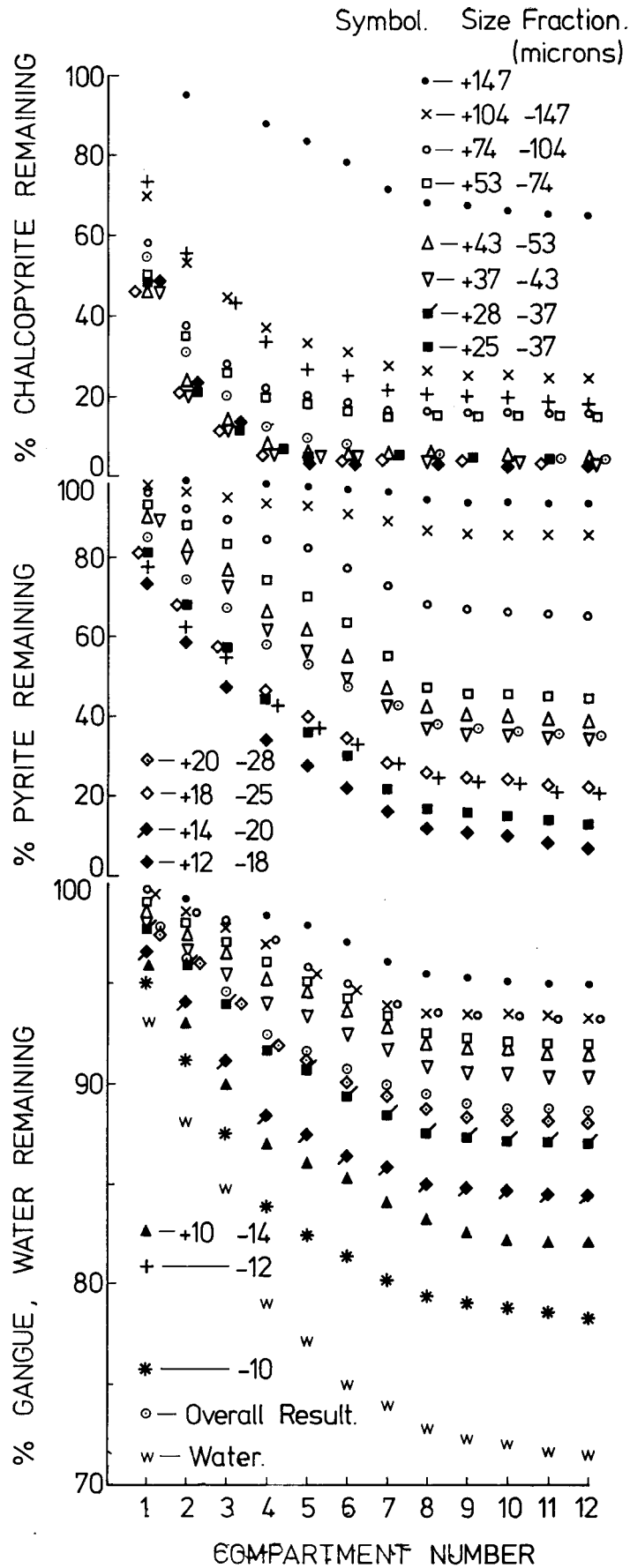
Fig. 2—Relationships between percentage of chalcopyrite, pyrite, and gangue
remaining and compartment number for various mineral size-fractions in the
Mount Isa plant rougher section. The relationship between percentage of water
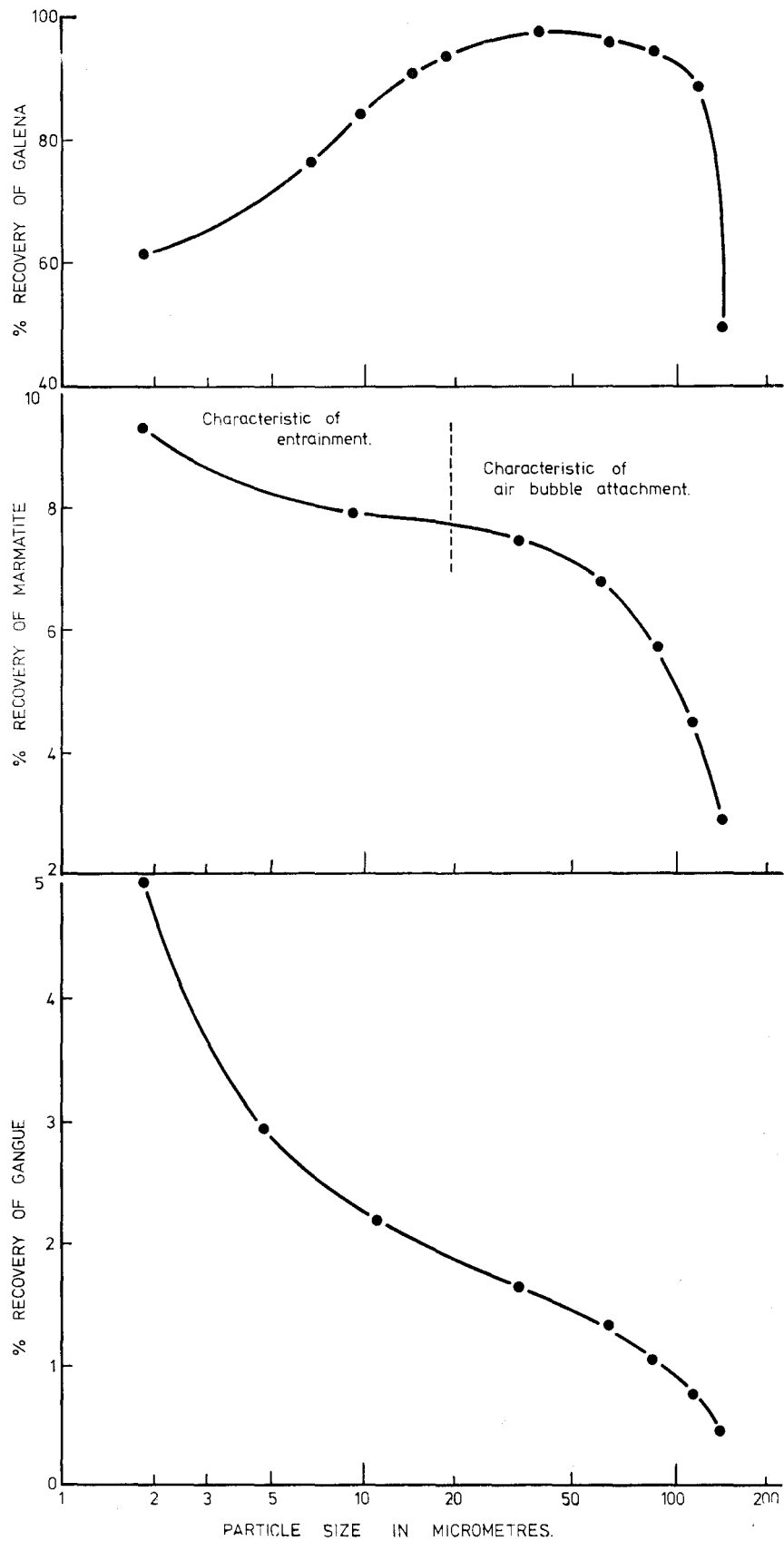remaining and compartment number is also shown

Fig. 3—The relationship between recovery after six rougher compartments and particle size for galena, marmatite, and non-sulphide gangue, NBHC lead rougher bank

in this discussion the term *non-sulphide gangue* will refer to these particles. Most published models for gangue recovery have used semi-empirical models that are identical to the published semi-empirical models for valuables. A low value for the first-order rate constant was assumed. Jowett[8] proposed a different type of model for gangue, which assumed that mechanical entrapment is the major mechanism for the recovery of gangue.

This hypothesis was investigated in JKMRC pilot-plant tests. Pure silica slurry was continuously floated with frother only at different pulp densities and at varying water recovery rates. The relationship between the recovery rates of water and silica is shown in Fig. 4. This figure gives strong support to the

importance of the water-entrainment mechanism for non-sulphide gangue. The relationship between the recovery rates of water and non-sulphide gangue for some operating plants is shown in Fig. 5.

There is also evidence that hydraulic classification occurs in the entrained pulp in the froth column, and this is illustrated in Fig. 6, which shows what may be regarded as the classification function for particles of non-sulphide gangue in different ores. It is probable that the particles in region A are predominantly free and those in region B are predominantly composite. The small particles enter the concentrate after being classified in the rising column of entrained water in the froth, and their behaviour can be described by a classification matrix that can be written

$$CF_i = \frac{\text{(Recovery rate of free gangue*/Recovery rate of water)}_{\text{Concentrate}}}{\text{(Mass of free gangue*/Unit mass of water)}_{\text{Pulp}}}$$
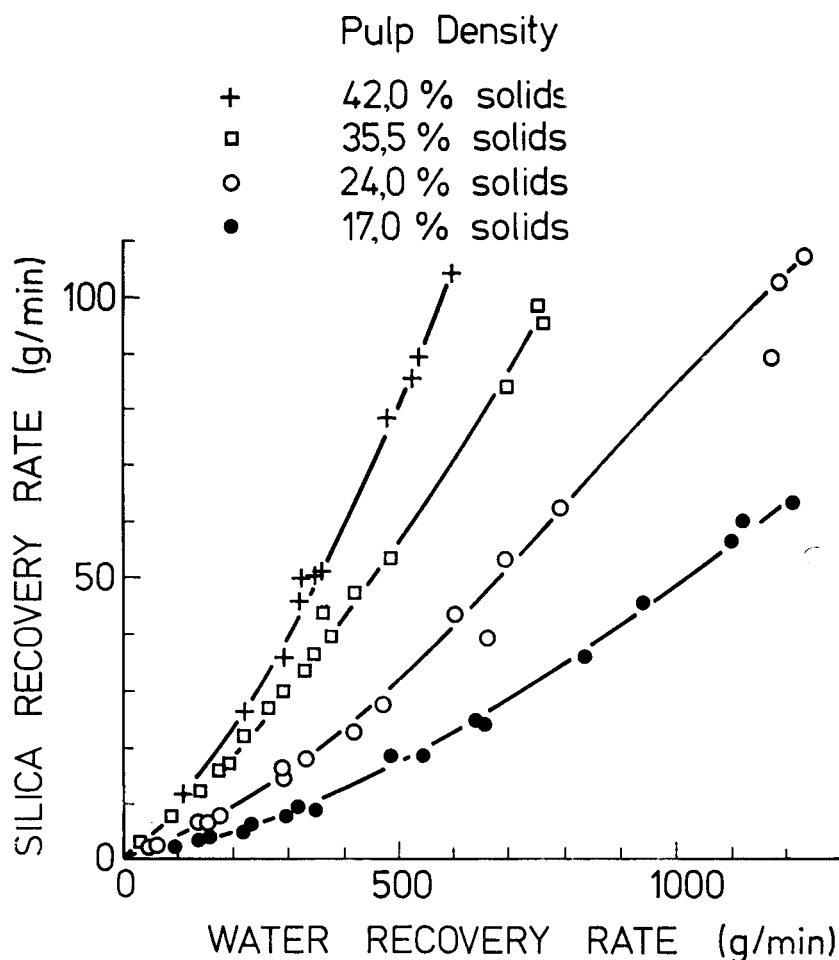
or
$$CF_i = (RRFG_i/RRW)/(MFGUWP_i)$$
$$\qquad \ldots \ldots \ldots (1)$$

for the ith size fraction.

This can be rewritten and summed over n size-fractions to give the equation

$$RRFG = RRW \cdot \sum_{i=1}^{n} CF_i \cdot MFGUWP_i. \qquad \ldots (2)$$

*in the ith size-fraction.

In equation (2), the quantity $(MFGUWP_i)$ is determined by the pulp density and sizing of the gangue in the compartments of a rougher/scavenger section. For each compartment, other variables (e.g., pulp level, air-addition rate, and frother addition) determine the water recovery rate (RRW) in equation (2). From the collected results it has been noted that values in the classification matrix (CF_i) for a particular type of free gangue are constant over a normal range of water recovery rates. Typical values are listed in Table III. The values in the classification matrix effectively express the efficiency of the water in transporting the various size-fractions of free non-sulphide gangue from the pulp, through the froth column, and into the concentrate.

Equation (2) can be modified to give an important alternative form:
$$RRFG_i = RRW \cdot CF_i \cdot MFGUWP_i. \qquad \ldots \ldots (3)$$
$$= \frac{RRW \cdot CF_i}{MWAT} \cdot MFG_i \qquad \ldots \ldots (4)$$
$$= k_i \cdot MFG_i. \qquad \ldots (5)$$

Equation (5) is simply the traditional first-order rate equation for the flotation process. However, if a rougher/scavenger bank is considered, the value of the rate constant for the ith size-fraction of gangue can be evaluated for each compartment from the quantities (RRW), $(MWAT)$, and (CF_i). It is important to note that the recovery rate of water is related to the physical variables in all operations and may change down a bank. This is the reason why a conventional rate equation to describe gangue behaviour must be treated with care.

This discussion has been confined

Pulp Density

+   42,0 % solids
□   35,5 % solids
○   24,0 % solids
●   17,0 % solids

Fig. 4—Relationship between the recovery rates of silica and water at varying pulp densities in a pilot-scale machine

Size-fraction (microns)		−420	−300	−210	−150	−75	−44	−33	−23	−16	−11
	+420	+300	+210	+150	+75	+44	+33	+23	+16	+11	
Value in classification matrix (CF_i)	0	0	0	0	0	,03	,04	,11	,24	,44	,83

to particles that do not adsorb collector in sufficient quantities to make them partially floatable. Some particles of non-sulphide gangue do float by adhesion to air bubbles, and the classification function is inadequate to describe their behaviour. These should really be treated in the same manner as the sulphide particles, but the problem of identifying these particles and describing them quantitatively has not yet been solved.

The importance of entrainment is implicitly recognized by flotation operators who vary pulp depths and air additions to cells as part of their normal operating routine. It is important that it should be explicitly recognized in simulation models and control systems, and, for this purpose, data on the flotation rate of water as well as the mineral species must be collected. It seems reasonable to suggest that this mechanism is just as important with oxide flotation as with sulphide flotation, but data for testing the hypothesis are not available.

Sulphide Valuables

The flotation of valuable sulphides is essentially a rate process. Woodburn and Loveday[17], Harris and Chakravarti[18], and others have proposed semi-empirical models using a continuous distribution of flotation properties. The equation that describes the process for a particular mineral in a single batch compartment is

$$M = M_0 \int_0^\infty e^{-kt} f(k,0)\, dk \quad . . \quad (6)$$

and in a continuous compartment is

$$M = M_0 \int_0^\infty \int_0^\infty e^{-kt} E(t) f(k,0)\, dt\, dk.$$
$$\cdots\cdots\cdots\cdots\cdots \quad (7)$$

The problem in using these equations, which are first-order and recognize the existence within a valuable component of species having different flotation properties, is to determine the form of the continuous distribution of rate constants.

Other authors (for example Imaizumi and Inoue[19], Kelsall[13])

have used a discrete approximation to the form of the continuous distribution:

$$FCR = \phi e^{-k_s t} + (1-\phi)e^{-k_f t}.$$

This approximation can be illustrated by reference to Fig. 2, in which it will be noted that each size-fraction of chalcopyrite can be regarded as containing fast- and slow-floating fractions, the major difference between the size-fractions being the proportion of the fraction that is slow floating. Kelsall described this behaviour for a copper ore in 1961, and it has since been found that the same comment can be made about the valuable minerals in many ores. Thus, the three parameters that describe the behaviour of the valuable mineral on a size-by-size basis are as follows:

(1) the flotation rate constant of the fast-floating fraction in each fraction (k_f),

(2) the flotation rate constant of the slow-floating fraction in each fraction (k_s), and

(3) the proportion of the slow-floating fraction (ϕ).

The approximation that each sulphide mineral exists in the ore wholly as fast- and slow-floating components can be demonstrated with respect to the Philex ore. Four surveys were carried out on the rougher/scavenger banks and, for each survey, the rate constants of the fast- and slow-floating fractions, and the proportion of slow-floating, were calculated from the following equation:

Recovery rate of chalcopyrite from a compartment
$$= k_f M_f + k_s M_s.$$

The results, and a comparison between the observed and calculated results for each survey, are given in Table IV.

The value of using this simple approximation in simulating the behaviour of the valuable sulphide minerals is evident.

Further results have shown that the recovery rate of water also in-

TABLE IV
COMPARISON OF OBSERVED AND PREDICTED VALUES OF PERCENTAGE RECOVERY FOR
VALUABLES IN THE PHILEX ROUGHER/SCAVENGER SECTION

	Rougher	First scavenger	Second scavenger	Third scavenger
Survey 10-12-70				
Observed	77,5	84,1	86,2	86,9
Predicted	78,9	83,3	85,5	86,9
Survey 12-12-70				
Observed	84,3	87,5	88,6	89,0
Predicted	83,0	86,9	88,8	90,0
Survey 17-12-70				
Observed	83,4	87,2	88,8	89,5
Predicted	82,7	86,5	88,5	89,6
Survey 22-12-70				
Observed	80,8	86,1	87,9	88,3
Predicted	81,5	85,4	87,5	88,8

	High rate constant (min⁻¹)	Low rate constant (min⁻¹)	Proportion of mineral with low rate constant
Survey 10-12-70	1,33	0,025	0,220
12-12-70	1,33	0,025	0,185
17-12-70	1,33	0,025	0,180
22-12-70	1,33	0,025	0,200

□ Mt. Isa rougher section.

• Mt. Lyell rougher section.

○ Philex rougher-scavenger section.

✕ Peko rougher-scavenger section.

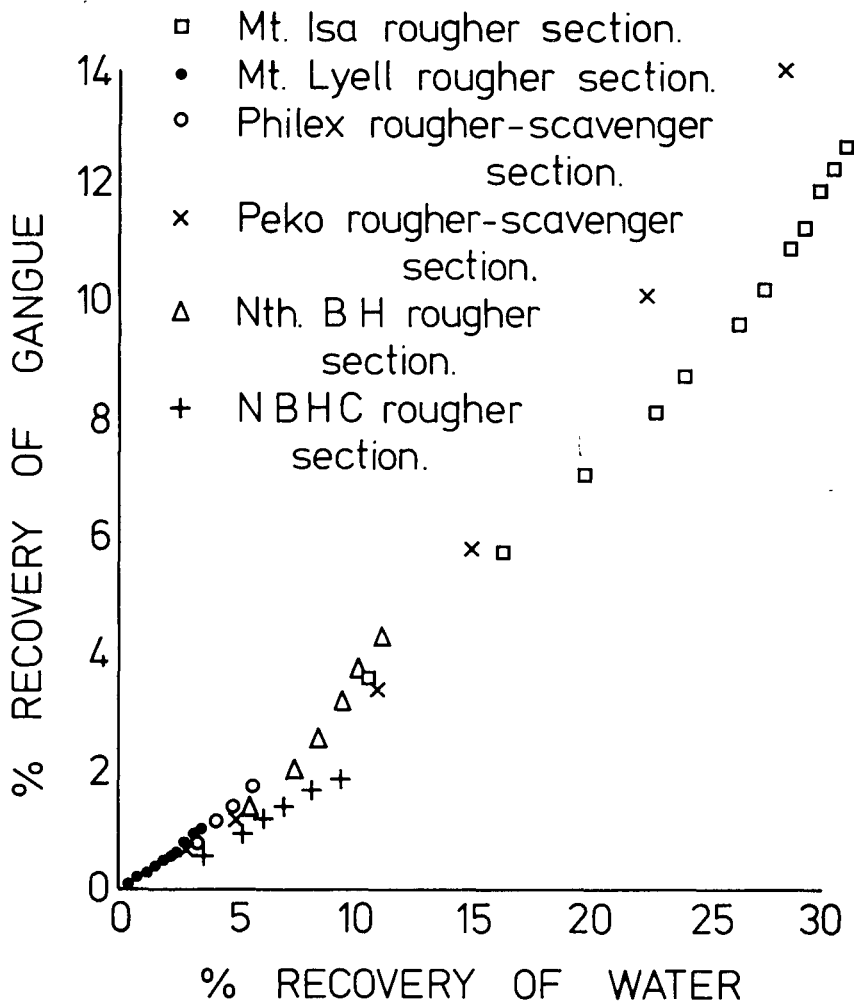△ Nth. B H rougher section.

+ N B H C rougher section.

Fig. 5—Relationship between recovery rates of non-sulphide gangue and water in several chalcopyrite and galena flotation processes

fluences the recovery rate of sulphide particles, and that the recovery of each sulphide mineral should be described by the equation

Recovery rate of mineral from a compartment (RRV)

$$= (k'_f + k_{fw})M_f + (k'_s + k_{sw})M_s.$$

$$\ldots \text{ (8)}$$

The rate constants k'_f and k'_s are the more basic rate constants, dependent on the chemical environment and obtained at a minimum water recovery rate. The rate constants k_{fw} and k_{sw} describe the contribution of the water-entrainment mechanism, which depends on the recovery rate of water controlled by the physical operation of the cell, i.e., froth depth, air addition, and frother addition.

The effect of varying water recovery rate on the recovery of a valuable by the entrainment mech-

anism can be described by a modified form of equation (4):

Recovery rate of fast floating valuable of size i by entrainment

$$= \frac{RRW}{MWAT} \cdot CF_i \cdot X_i \cdot M_f,$$

$$\ldots \text{ (9)}$$

where X_i = proportion of fast-floating valuable in the ith size fraction.

Over n size fractions,

Recovery rate of fast-floating valuable by entrainment

$$= M_f \cdot \frac{RRW}{MWAT} \cdot \sum_{i=1}^{n} CF_i \cdot X_i$$

$$= M_f \cdot k_{fw}. \quad \ldots \ldots \text{ (10)}$$

By substitution of the values of k_{fw} and a similarly derived k_{sw} in equation (8),

$$RRV = (k'_f + \frac{RRW}{MWAT} \cdot \sum_{i=1}^{n}$$

$$CF_i \cdot X_i)M_f + (k'_s + \frac{RRW}{MWAT} \cdot$$

$$\sum_{i=1}^{n} CF'_i \cdot Y_i)M_s,$$

$$\ldots \text{ (11)}$$

where Y_i = proportion of slow-floating valuable in the ith size fraction.

This is the proposed model for the recovery of sulphide minerals. It incorporates the recovery rate of water, which has been observed to affect the rate of recovery of valuables. Experimental studies of the effect of entrainment on the rates of flotation are to be carried out. The elements of the classification matrices will be determined in a series of steady-state pilot-scale tests.

It is clear that the method of representing a comminuted sulphide mineral in terms of fast- and slow-floating fractions is a considerable simplification of the real case. Despite this, the approximation gives a model that is simple and that accurately describes the behaviour of the valuable sulphides in several different ores, and it appears to be of general use.

Sulphide Gangue

The behaviour of gangue sulphides has been observed to be similar to that of valuable sulphides, but the rates of flotation are lower. The rate of recovery of water has a larger proportional influence on the rate of recovery of gangue sulphides than of valuable sulphides. This can be explained by the greater importance of the water-entrainment recovery mechanism for gangue sulphides.

Summary

Some of the features common to sulphide flotation processes are as follows.

(a) The valuable sulphides can be regarded as containing fast-floating and slow-floating fractions, and the total rate of flotation is a function of the behaviour of these fractions and the rate at which water is recovered.
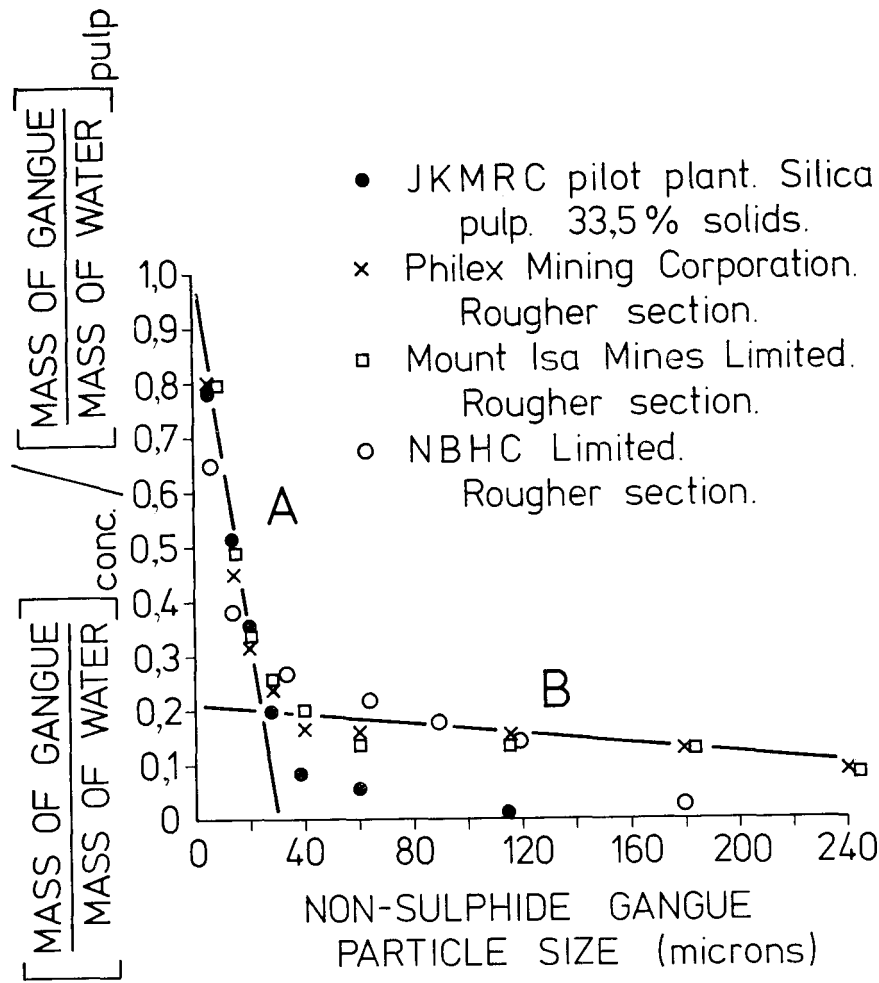
Fig. 6—Relationship between the classification function, which describes hydraulic classification in the entrained pulp in the froth column, and particle size for gangue in several sulphide rougher sections

(d) The free particles of non-sulphide, siliceous gangue enter the concentrate by an entrainment mechanism, and a hydraulic classification mechanism operates while they are retained in the froth. Their recovery rates can be related to the recovery rate of water.

CONTROL OF SULPHIDE FLOTATION PROCESSES

Alternative control objectives can be constant concentrate grade at maximum mineral recovery, maximum grade at constant recovery, maximum throughput at some required grade and recovery, optimization of reagent usage, economic optimization of circuit performance, or some combination of these. The primary function of the control scheme is to detect a disturbance and to alter the control variables to maintain the control objectives. Reagent additions are frequently used as control variables, and the level of control varies from manual adjustment to digital control such as is used at the Ecstall concentrator (Amsden et al.[20]).

Disturbances to the process may include changes in feed grade or ore type. If the disturbance is a change only in feed grade, a change in reagent addition may be sufficient to allow for the altered mass of sulphide in the pulp. Changes may also be necessary in the physical variables if the correct flowrates of concentrates are to be maintained, particularly where there is a heavy

(b) The gangue sulphides behave in a similar manner to the valuable sulphides, except that the flotation rate constants are markedly reduced.

(c) The composite particles appear to behave as slow-floating sulphide particles, although the slow-floating fractions may also contain some liberated particles, particularly in the very fine fractions.
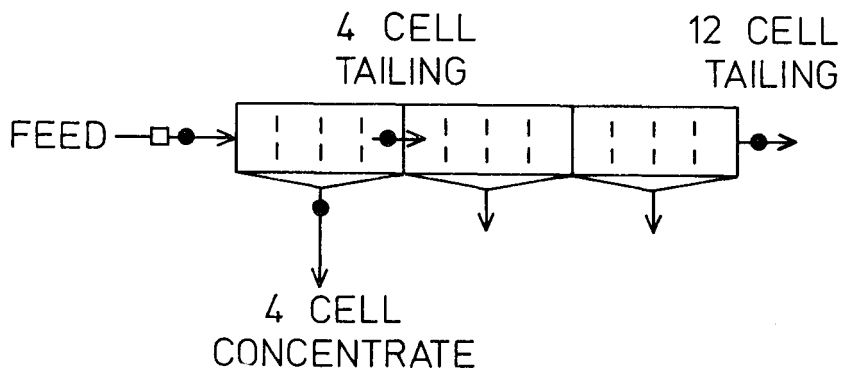

Fig. 7—The typical responses of valuable and gangue sulphide recoveries to collector addition

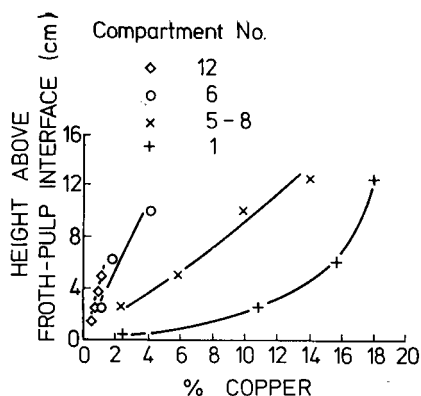**Fig. 8—Instrumentation on the test rougher bank at Mount Isa**

Fig. 9 — Relationship between copper assays and height above the froth-pulp interface for concentrate from various points in Mount Isa rougher bank

flow. Assays of the feed and bank tailing may be sufficient in this case for corrective action. If, on the other hand, the disturbance is a change in ore type, it is likely that a different chemical environment is necessary to give best flotation performance. In the semi-empirical model, the proportion of slow-floating mineral (ϕ) must be altered. A feed and tailing assay is not sufficient to allow corrective action. It has been found in plant tests (Lynch[21]) that the first few cells in a bank suitably equipped with sensing instruments can be used as an on-line detector of changes in ore floatability, i.e., ore type.

Importance of Chemical and Physical Control Variables

To effectively control a sulphide flotation process, both the physical and chemical variables should be incorporated in the control scheme. The chemical variables are most useful for altering the rate of recovery of particles by the selective-attachment mechanism. Most flotation control schemes use reagents as the control variables; for example, Ecstall,¦NBHC (Presgrave[22]), Lake Dufault (Smith and Lewis[23] and Lewis[24]), and Tennessee Copper's London mill (Faulkner[25]). Control of the chemical environment is an essential part of any control scheme.

The typical response of sulphide mineral recovery to a change in collector concentration is shown in Fig. 7. In many control schemes, an attempt is made to minimize reagent consumption and maximize concentrate grade by operating as close as possible to the edge of the plateau

region on the curve for valuable sulphides. A scheme for the monitoring of circuit feed and of concentrate and tailing assays, and for the systematic variation of reagents in a search for the optimum grade-recovery point has been implemented successfully at the Ecstall concentrator[20]. This was a major advance in the evolution of control schemes.

In other plant testwork, the control of the physical variables has been found to be necessary to minimize the water recovery rate, which affects the recoveries of sulphide and non-sulphide gangues by the entrainment mechanism (Thorne[12] and Lynch[21]). It was shown that it is possible to vary the grade-recovery curve for a particular mineral by manipulation of the variables that control only the froth behaviour, without alteration of the chemical environment. Since this work confirmed the importance of the entrainment mechanism, it will be discussed here in more detail.

Experimental Systems

The testwork was conducted in the No. 1 copper concentrator at Mount Isa during the period December 1972 to April 1973, and also in the lead-zinc concentrator at NBHC at Broken Hill during the period February to May 1973. The chalcopyrite flotation circuit in the No. 1 concentrator at Mount Isa included six open-circuit Fagergren banks in parallel. One bank was set up for the test programme with the instrumentation shown in Fig 8. A Hewlett Packard 2100A digital computer was used for data collection and processing on-line. It was not possible to vary the air addition to the cells, but the froth behaviour
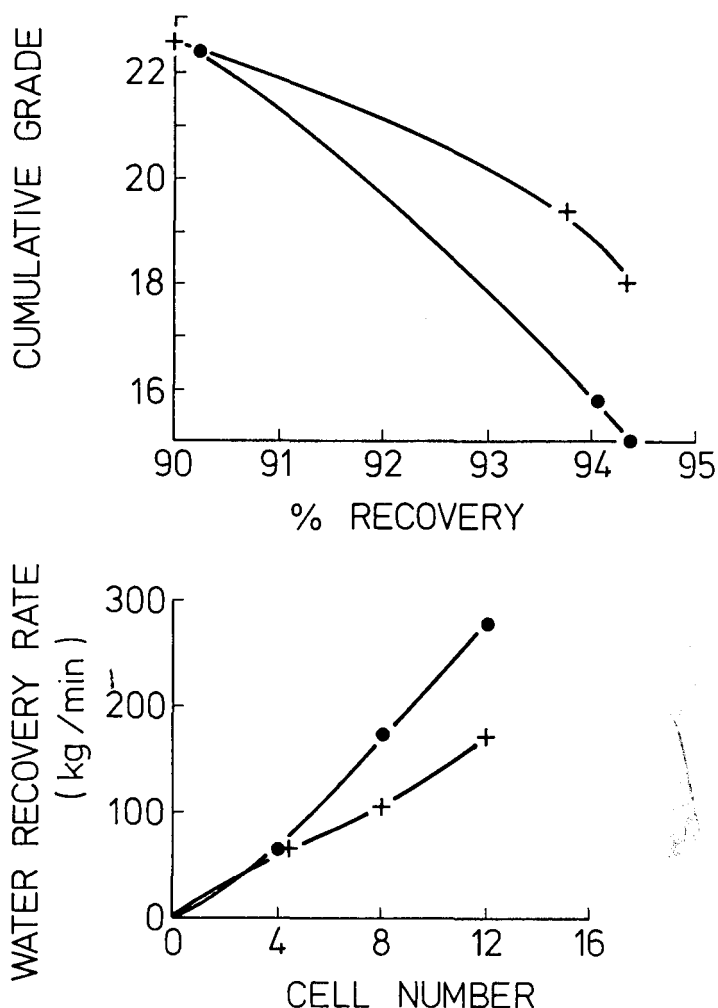

Fig. 10—The influence of change in water recovery rate on the copper grade-recovery curve, Mount Isa rougher bank
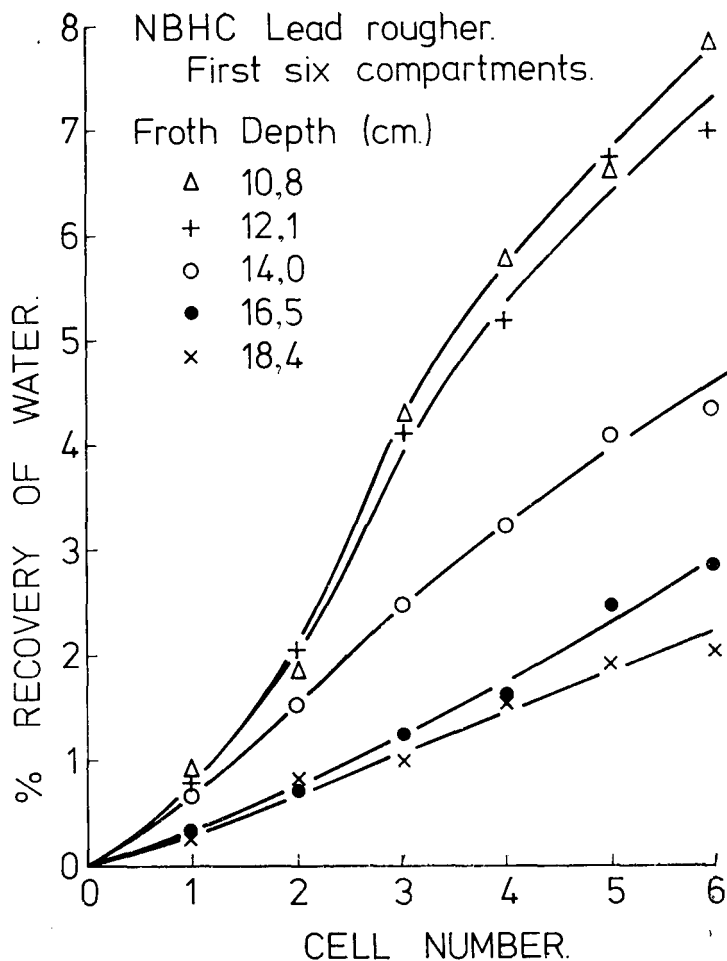
Fig. 11—The effect of change in froth depth on water recovery from the NBHC rougher bank

was changed by alteration of froth depth.

In the galena flotation circuit at NBHC, the test bank was an open-flow rougher bank of Denver 21 machines, which treated about 35 per cent of the total rougher feed. The only measuring instrument on the bank was a magnetic flowmeter on the feed line. In this case also, froth behaviour was changed by alteration of the froth depth.

Steady-state Results

The relationship between height above the froth-pulp interface and copper assay for froths from various points in the Mount Isa rougher bank is shown in Fig. 9. This shows qualitatively the importance of the froth as a concentrating region in the cell.

The influence of change in water recovery rate, obtained by change in froth height, on the grade-recovery curve for the Mount Isa rougher bank is shown in Fig. 10.

The improvement in the grade-recovery curve with decreased water recovery is the result of an increased drainage from the froth of particles that arrived there by entrainment. The effect of change in froth depth on the water recovery rate in the NBHC rougher bank is shown in Fig. 11, and on the selectivity of separation of galena from marmatite in Fig. 12. The improvement in selectivity with increasing froth depth is due to the increased preferential drainage from the froth of that fraction of the gangue sulphide (in this case marmatite) which reached the froth by entrainment.

On-line tests

On-line tests were carried out at Mount Isa in which the froth depth was varied and the effect on the concentrate grade and recovery was observed continuously. A typical result is shown in Fig. 13. It is clear

that the water recovery can be controlled to optimize grade.

CONCLUSIONS

The observed behaviour of minerals in sulphide flotation processes has been described. Models that recognize the importance of the water-entrainment mechanism have been discussed. Plant testwork has shown that it is possible to optimize the grade-recovery curve by careful control of the water recovery rate, and that control of the water recovery rate should be an integral part of a flotation control system.

ACKNOWLEDGEMENTS

NOMENCLATURE

CF_i	the ith element of the classification matrix describing the hydraulic classification of mineral particles during their passage through the froth column
RRW	recovery rate of water
$RRFG$	total recovery rate of free gangue
$MWAT$	mass of water in a compartment
MFG_i	mass of free gangue in the ith size-fraction in a compartment
k_i	rate constant for the ith size-fraction of gangue
M	mass of mineral in a batch compartment, or flowrate of a mineral in the tailing from a continuous compartment (mass/time)
$E(t)$	residence time distribution of solids (in tailings exit)
M_o	mass of mineral initially in a batch compartment or flowrate of a mineral in the feed to a continuous compartment (mass/time)
k	first-order rate constant for a mineral
FCR	fraction of component unrecovered after time t
M_f, M_s	mass of sulphide mineral in the pulp of a compart-

ment with high and low rate constant respectively The other symbols used in this paper are defined in the text.

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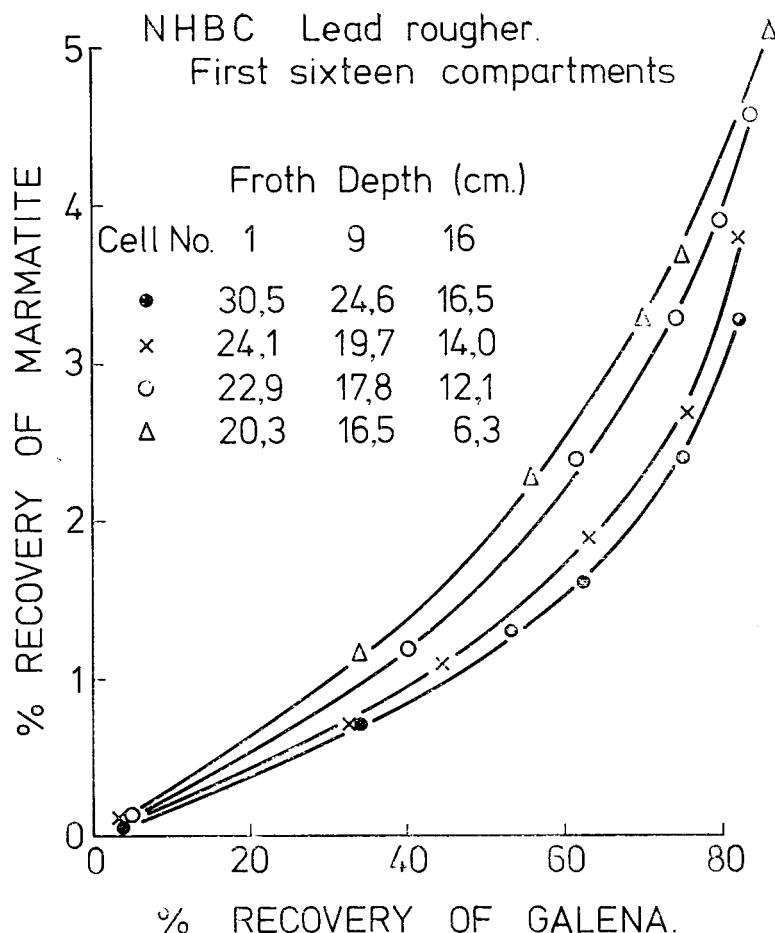
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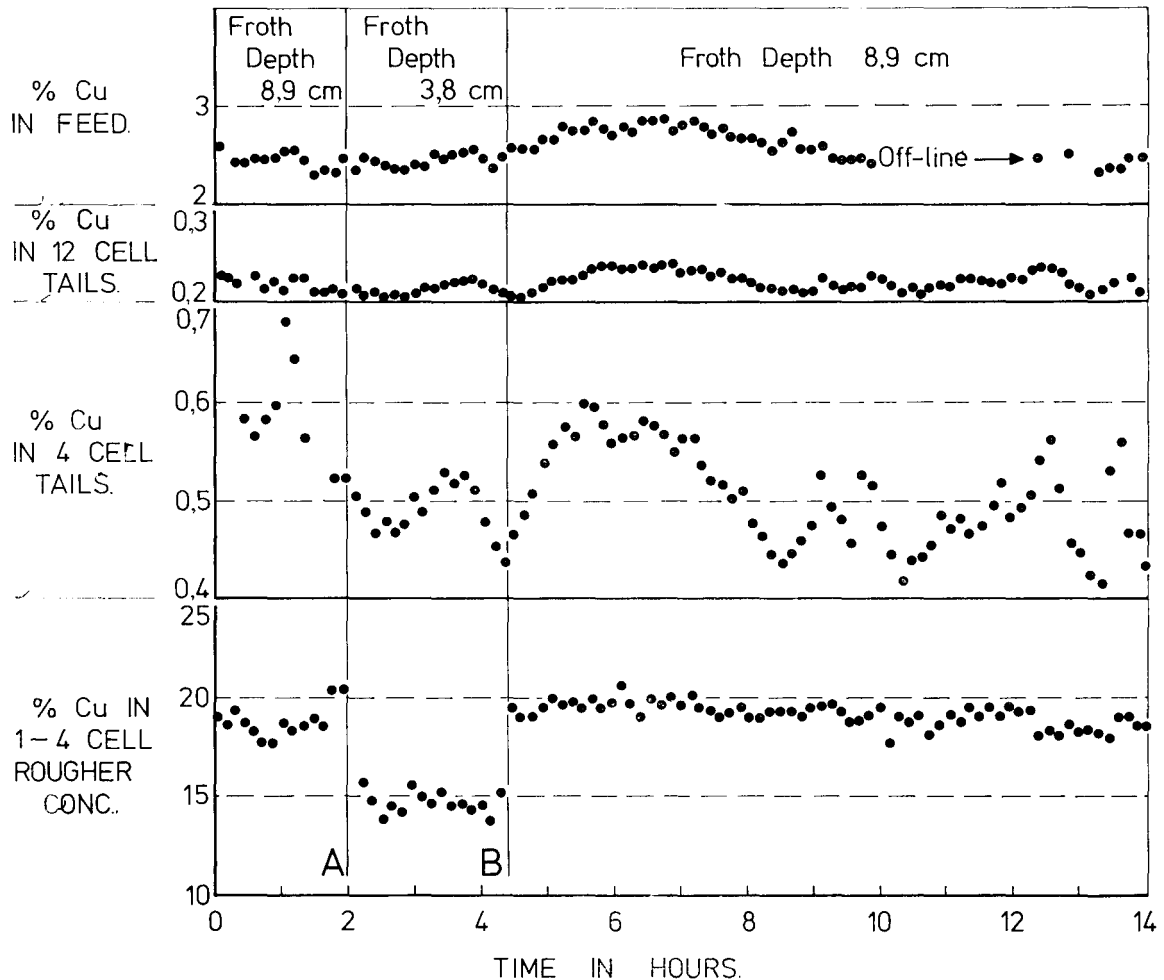
Fig. 12—The effect of change in froth depth on the selectivity curve describing galena/marmatite recovery in the NBHC lead rougher bank.

Fig. 13—Results from the No. 5 copper rougher bank, Mount Isa, to demonstrate the effect of change in froth depth on the process.

Book review

Ramsey, Robert H. **Men and mines of Newmont. A fifty year history.** New York, Octagon Books, 1973. $11.00.

It is interesting to consider how one man can influence a development by courage, luck, and perseverance. This is largely the story of how Colonel Walter Boyce Thompson and his later associates, dating from the year 1921, founded a mining and finance empire; a previous company started in 1916 apparently gave him the experience to go on to bigger things despite earlier set-backs. Hence, he envisaged that Newmont, with an initial capital of $8 million, would be a trading vehicle for his many promotions. It has since (1971) become a company with a market value of $950 million spread over 24 million ordinary shares.

The other chief executives who largely helped towards this achievement were Charles F. Ayer (a lawyer), Fred Searls (a metallurgist), Plato Malozemoff (a financier), and Marcus D. Banghart (a mining engineer, who spent some time in Southern Africa).

Newmont's largest project is perhaps San-Manuel-Magma Copper Mine in Arizona. It also has access to many others: *inter alia*, Kenne-cott and Texas Gulf Sulphur in Canada; O'Okiep, Tsumeb, and Palabora in South Africa; elsewhere, to U.S.A. companies like Homestake, Hanna, etc., through the association of one-time Newmont personnel (e.g., John Gustafson). This indicates a spirit of co-operation on a global scale that has paid handsome dividends.

All are mentioned in a skilfully woven tale of success and failures by the author, who was a Metallurgical Consultant to Newmont and is now a member of the staff in New York.

J.T.M.

NIM Reports

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Report No. 1567

Estimation of the parameters in the distributed-constant flotation model.

A complete system is developed for the estimation, from batch or continuous data, of the parameters in the distributed-constant flotation model. Various hypotheses concerning the model are tested, and a description is given of a method by which a particular slurry can be adequately and significantly characterized from available data.

The model can predict total recovery as a function of residence time, but is not able to predict the particle-size distribution of the concentrate. The incorporation of a simple model for froth behaviour results in a marked improvement in this respect.

Report No. 1591

The inductive measurement of conductivity in slags.

An investigation of the use of the inductive-loop method for the determination of conductivity in slags resulted in the design of several instruments. The development of the different systems is described, and the advantages and disadvantages of the various types of instruments are discussed.

Report No. 1609

An interlaboratory analysis of two ferrochromium slags.

This report describes the analyses, by ten different laboratories, of two slags, one associated with the production of high-carbon ferrochromium, and the other with the production of ferrochromium-silicide. The results, their statistical treatment, and the methods of analysis used are given. Preferred values are assigned to the two samples.

Report No. 1611

The X-ray-fluorescence determination of percentage concentrations of niobium and tantalum in ores and minerals.

This report describes the investigational work in the development of a procedure for the determination of tantalum and niobium in ores where the concentration of either element exceeds 0,5 per cent. The samples are decomposed by the use of a flux that incorporates two internal standards, and the technique obviates the need for the determination of backgrounds and corrects for matrix effects. Calibration is achieved by means of synthetic standards. The precision of the method compares well with chemical methods, and the time required is much less.

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