

DETERMINATION OF THE CONTRIBUTIONS BY TRUE FLOTATION  
AND ENTRAINMENT DURING THE FLOTATION PROCESS

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ABSTRACT

A comparison is made of three methods for the determination of the contributions made by true flotation and the entrainment of mineral particles during the flotation process. In the first method, size-by-size recoveries are measured in both the presence and the absence of a collector. It is assumed that, at the same water recovery, the same mass of material is recovered by entrainment. The second method involves a number of batch flotation tests in which both the mass of solids and the water that is recovered after a given time is varied by changing the rate of froth removal and the depth of the froth. The regression line of the relationship between mineral recovery and water recovery is extrapolated to a zero water recovery, and the intercept on the mineral-recovery axis is then taken as the mass

of particles that was recovered by true flotation. The third method describes the differential classification of entrained solids and water during flotation by a transfer factor,  $X_i(t)$ . This factor is calculated from the recovery of solids and water, and from the changes in the composition of the pulp and the characteristics of the froth with time during a single batch flotation test. The amount of material that is floated is obtained from the calculated amount of entrained material and the total measured mass of solids recovered in any specific time interval.

Laboratory-scale batch flotation tests in a mechanically agitated cell were carried out on an artificial mixture of pure pyrite and gangue material from different sources. The amount of material that was floated in each case was calculated according to the methods described above. The discrepancies in the calculated amount of floated material show that any specific method should be used carefully. The discrepancies are further analysed in terms of the assumptions made in the various methods, and the major areas of application of each method are identified.

## 1. INTRODUCTION

Laboratory-scale batch flotation tests play a very important part in the optimization of the flotation process. Such tests are often used in investigations of the effect of flotation reagents such as collectors, frothers, and modifiers on the efficiency of the flotation process before

these reagents are tested or used on an industrial scale. Likewise, an indication of the effect of particle-size and head-grade of the feed material on the metallurgical performance of a large-scale plant can be obtained by the flotation of a representative sample of ore in a laboratory-scale batch cell. Normally, it is also the first step in the scale-up of flotation cells to an industrial scale, and serves as a measure in the determination of the residence time that will be required for a given recovery from any particular ore that is floating at a certain rate. It is therefore very important that the data that is obtained from a batch flotation test should be interpreted correctly, so that it can be of use in the development or the optimization of flotation operations. These experiments should also be planned in a way that allows the generation of enough useful information to enable unambiguous conclusions to be drawn.

The efficiency of the flotation process is determined mainly by the amount of material that is recovered by true flotation, i.e. the particles that are physically attached to the surfaces of the bubbles by virtue of their hydrophobicity. The selectivity of flotation is another important factor that depends on the extent to which unwanted or gangue particles are entrained with the water into both the froth and the concentrate. In order that the results of batch flotation tests can be correctly interpreted, it is important that a reasonable estimation of true flotation and entrainment can be made.

In recent years, three major methods have been proposed for the separation of the contributions of true flotation and the entrainment of mineral particles during batch flotation tests. A brief description of these methods is given below, and an analysis of their respective advantages and disadvantages will be given later in this work.

#### Method 1.

A method was proposed by Trahar (1981) in which the recoveries of solids and water are measured during two batch flotation tests - one in the presence of a collector, and the other in the absence of a collector. It is assumed that, at the same water recovery (normally obtained after different times of flotation under such conditions since the rates of recovery are different), the amount of material that was recovered by entrainment is the same. The amount of material recovered by true flotation (assumed to occur only in the presence of a collector) can therefore be calculated from the difference between the mass of solids that was recovered in the presence and in the absence of the collector, at the same water recovery. This method is therefore suited to the study of the rate of true flotation. A schematic representation of the procedure involved in this method is given in Figure 1.

#### Method 2.

Warren (1985) proposed a method in which the recoveries of mineral particles and water after a given time  $t^*$  of flotation are correlated in the determination of the respective masses of particles that were recovered by true

flotation and by entrainment. A number of batch flotation tests are involved in which the amounts of solids and water that are recovered are varied by changing the rate of froth removal and the depth of the froth. The regression line of the relationship between mineral recovery and water recovery is extrapolated to a water recovery of zero, and the intercept on the mineral-recovery axis is interpreted as the recovery that occurs as a result of true flotation. If the flotation interval  $t^*$  is short enough to allow most, but not all, of the easily floatable solids to be recovered, a linear relationship exists between the amount of material that is entrained,  $m_{ei}(t^*)$ , and the amount of water that is recovered in the same interval,  $m_{eq}(t^*)$ , i.e.

$$m_{ei}(t^*) = \beta_i(t^*) m_{eq}(t^*) \quad [1]$$

The term  $\beta_i(t^*)$  is often referred to as the 'degree of entrainment', and has been found to range from 0,72 [quartz >3,5  $\mu\text{m}$ , Trahar (1981)] to 0,99 [silica <12  $\mu\text{m}$ , Engelbrecht and Woodburn (1975)] for ultrafines. The degree of entrainment decreases with an increase in particle size, and has values that range from less than 0,1 [quartz >40  $\mu\text{m}$ , Engelbrecht and Woodburn (1975)] to 0,03 [phosphate ore, -150+75  $\mu\text{m}$ , Ross (1988)].

The total cumulative amount of species  $i$  that is recovered over a time interval  $t^*$  occurs as a result of the contributions of true flotation and entrainment, i.e.

$$\begin{aligned}
m_{t_i}(t^*) &= m_{f_i}(t^*) + m_{e_i}(t^*) \\
&= m_{f_i}(t^*) + \beta_i(t^*) m_{e_q}(t^*)
\end{aligned}
\tag{2}$$

Figure 2 gives a schematic representation of the procedures in this method.

### Method 3.

The method proposed by Ross (1988) involves only one batch flotation test, in which the recoveries of solids and water, and the consequent changes in the composition of the pulp and the characteristics of the froth with time, are used in the calculation of a transfer factor,  $X_i(t)$ , for entrained particles that belong to species  $i$ . The transfer factor describes the differential classification of entrained solids and water during flotation, and is defined as

$$X_i(t) = \frac{m_{e_i}(t) C_{\tau q}(t)}{m_{e_q}(t) C_{\tau i}(t)}
\tag{3}$$

where  $m_{e_i}(t)$  and  $m_{e_q}(t)$  are, respectively, the masses of entrained solids and water that are recovered in a specific time interval  $t$ , and  $C_{\tau q}(t)$  and  $C_{\tau i}(t)$  are the corresponding concentrations (in grams per litre of pulp) of water and solid species  $i$  in the pulp. If the level of the pulp is kept constant during the batch flotation test by the addition of make-up water, the concentration,  $C_{\tau i}(t)$ , of solid species  $i$  in the pulp at any time  $t$  can be expressed as

$$C_{\tau i}(t) = \frac{W_{ip}(0) - W_{ic}(t)}{W_{qp}(0) + \sum W_{ip}(0)/\rho_i} \quad [4]$$

where  $W_{ip}(0)$  and  $W_{qp}(0)$  are the mass (g) of species  $i$  and water in the pulp at time  $t=0$  respectively.  $W_{ic}(t)$  is the cumulative mass of species  $i$  that is recovered in the concentrate, and  $\rho_i$  (g/cm<sup>3</sup>) is its density.

The value of the transfer factor  $X_i(t)$  is determined from the relationship  $Y_i(t)$  between the *total* masses of solids and water that are recovered during flotation, as described below. Similarly to equation (2), the value of  $Y_i(t)$  can be expressed as

$$Y_i(t) = \frac{m_{ti}(t) C_{\tau q}(t)}{m_{eq}(t) C_{\tau i}(t)} \quad [5]$$

where  $m_{ti}(t)$  (in grams) is the total mass of solids recovered in any specific time interval  $t$ . The mass  $m_{fi}(t)$  of particles that were recovered by true flotation can then be calculated from the total mass  $m_{ti}(t)$  and the mass  $m_{ei}(t)$  that was recovered by entrainment, viz

$$m_{fi}(t) = m_{ti}(t) - m_{ei}(t) \quad [6]$$

It is assumed that only entrained solids are recovered at the end ( $t \rightarrow t_\infty$ ) of the batch flotation test, i.e.

$$X_i(t) = Y_i(t) \quad \text{when } t \rightarrow t_\infty. \quad [7]$$

In other words, it is assumed that the recovery of water at a concentration of  $C_{Tq}(t)$  in the pulp reflects the recovery of entrained solids at a concentration of  $C_{Ti}(t)$  at any time  $t$  during a batch flotation test. Values of  $X_i(0)$  at the start of a batch flotation test have been found to range from 0,09 (pyritic sulphide ore, -150+75  $\mu\text{m}$ ) to 0,55 [pyritic sulphide ore, -38  $\mu\text{m}$ ; Ross (1988)]. Evidence exists to suggest that the value of  $X_i(t)$  also depends on the nature of the froth. A phosphate ore was floated under conditions similar to those for the pyritic sulphide ore (forming a more stable froth), and the values of  $X_i(0)$  were 0,11 and 0,76 respectively for the corresponding size fractions. A schematic representation of this method, subsequently referred to as Method 3, is given in Figure 3.

The present work compares the results from each of the three methods described above, and attempts to analyse them in terms of the assumptions made. An attempt is also made to identify the major areas in which the respective methods can be applied most successfully.

## 2. EXPERIMENTAL

All the experiments in this investigation were carried out in a Leeds open-top laboratory flotation cell with a nominal volume of 3,2 litres and a cross-sectional area of 203  $\text{cm}^2$ .

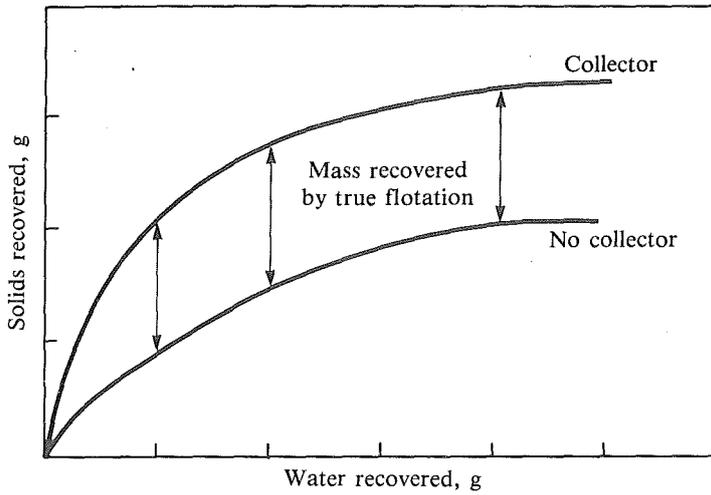


Figure 1 The determination of the mass of particles recovered by true flotation according to Method 1

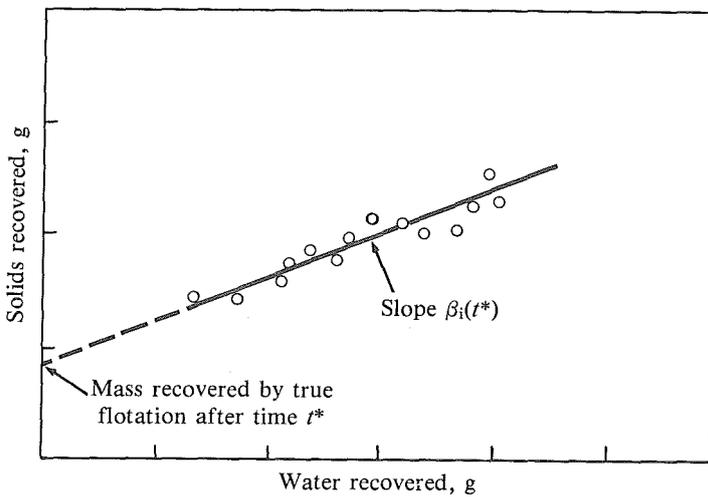


Figure 2 The determination of the mass of particles recovered by true flotation according to Method 2

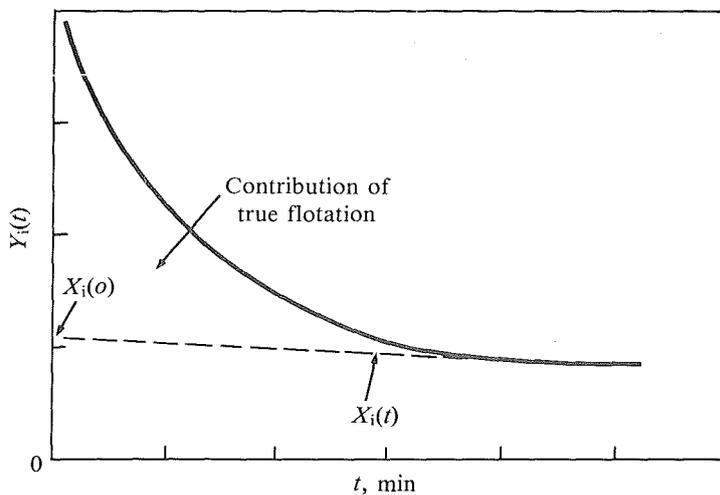


Figure 3 The determination of the mass of particles recovered by true flotation according to Method 3

The cell has a bottom-driven impeller that facilitates the unobstructed removal of concentrate. An artificial mixture of pure pyrite and gangue material from different sources was made up for each flotation test. The composition of the feed material and the particle size distribution is given in Table 1.

Table 1 Composition and particle size distribution of the feed material used in the batch flotation tests.

Size, $\mu\text{m}$	Mass percentage			
	Origin and nature of gangue material	Delmas silica sand	Unisel thick. underflow	Lorraine khaki shale
+212		85,05	1,08	-
-212+150		10,60	11,60	0,38
-150+106		2,19	36,13	4,23
-106+ 75		0,88	25,04	16,52
- 75+ 53		0,71	19,46	61,88
- 53+ 38		0,41	5,09	12,88
- 38		0,17	1,60	4,11
Mass % of feed <sup>†</sup>		93,40	93,40	5,50

<sup>†</sup> The feed consisted of either pyrite, silica sand and khaki shale, or pyrite, thickener underflow, and khaki shale. The size of the pyrite, which constituted 1,1 % of the feed mass in each case, was 100% -106+75  $\mu\text{m}$ .

The amount of material that was floated (according to method 2) was determined by the variation of the initial volumes of

pulp in the cell. In each case, the density of the pulp (i.e. 26,7 percent solids by mass) at the start of the flotation test was kept constant by the variation of the initial amount of solids in the same ratio as the water. The dosage of collector (Senkol SK50) was kept constant at 50 g/t while the frother (Dowfroth 250) was kept constant at a concentration of 7,5 mg per litre of liquid. When Method 1 was used in the determination of the amount of floated material, one test was carried out at the reagent dosages given above, while the other was conducted in the absence of a collector but with a frother at a dosage of 7,5 mg per litre of liquid. The pulp was first conditioned with collector at a pH value of 4,5 for 4 minutes, and then with frother for a further 2 minutes. After this, the air was turned on. The impeller speed and aeration rate were kept constant at 1200 r/min and 6 l/min respectively. Time  $t=0$  was taken as the instant the froth overflowed into the first froth collecting tray. The froth was removed at a constant, controlled rate of 10 scrapes per minute, the entire surface of the froth being covered with each scrape. Timed samples were obtained at cumulative flotation times of 0,25, 0,5, 1, 2, 4, and 8 minutes. The relationship between the froth depth (which was kept constant for each test by the addition of make-up water) and the initial volume of water in the batch flotation cell is given in Table 2.

Table 2 Relationship between the initial volume of water in the flotation cell and the depth of the froth.

Run no.	Initial volume of water, litres	Froth depth (cm)	
		Silica sand	Thick. underflow
1	2,3	2,2	2,1
2	2,4	1,6	1,5
3	2,5	1,0	0,9
4	2,6	0,5	0,4

### 3. RESULTS

Figure 4 gives the recoveries of solids and water in both the presence and in the absence of a collector when Delmas silica sand was used as the major gangue material. The total amount of solids that were recovered (after a flotation time of 8 minutes) increased slightly when the depth of the froth was decreased, i.e. when the initial volume of water in the flotation cell was increased. The recovery of water increased accordingly. A linear relationship was observed to exist, in the absence of collector, between the recoveries of solids and water at a froth depth of 0,5 cm. A very brittle and unstable froth was formed under these conditions, and its depth was the same as the depth when collector was used at the same initial volume of water. The recovery of solids dropped markedly, and the total amount of water that was recovered after a flotation time of 8 minutes increased slightly.

The corresponding results that were obtained when the Unisel thickener underflow was used as the major gangue material are given in Figure 5. Similar trends were followed to those with the silica sand. However, the comparison of these results with those given in Figure 4 shows that the recoveries of both solids and water were significantly higher than those obtained when the coarse silica sand was used as gangue. This was to be expected since the Unisel thickener underflow was significantly finer than the silica (Table 1), and the amount of entrained material would therefore have been higher. Again, the recovery of solids was markedly lower in the absence of collector at a froth depth of 0,4 cm but, unlike the results obtained for the silica sand, it was not related linearly to the recovery of water over the total cumulative flotation time of 8 minutes.

Figure 6 illustrates the changes that occur in the values of parameter  $Y_i(t)$  (used in Method 3) with operating conditions when the Delmas silica sand was used as the major gangue component. It must be noted that, although in this investigation the total amount of solids is considered to belong to the same single species, the same method of analysis can be applied to both individual size fractions and the various minerals such as pyrite and silica. The values of  $Y_i(t)$  decreased more sharply with time during the initial stages of flotation when the depth of the froth was increased. These results suggest that the rate of true flotation decreased with an increased froth depth. Furthermore, after the same cumulative flotation time, the values of

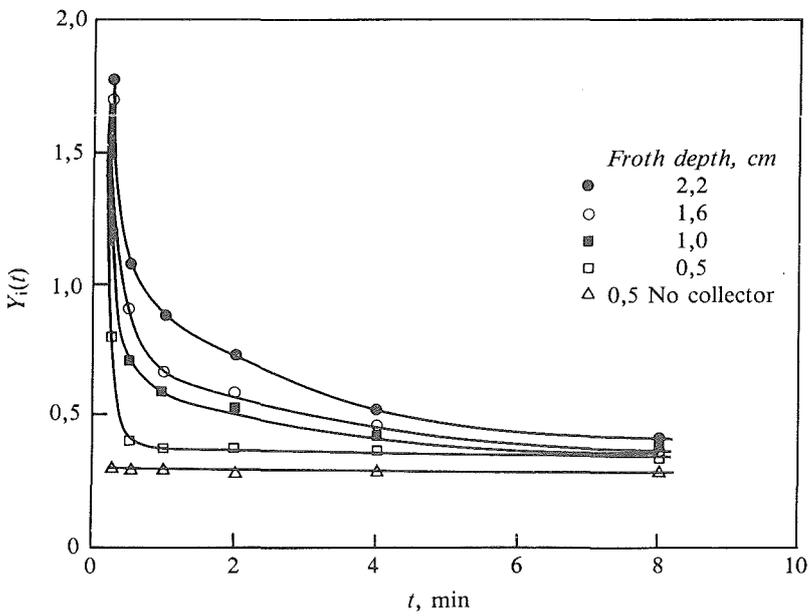
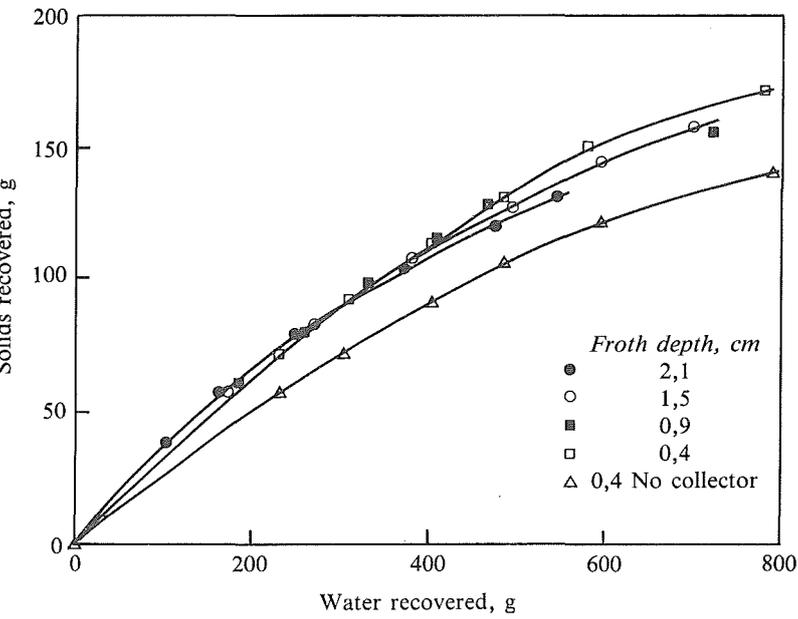
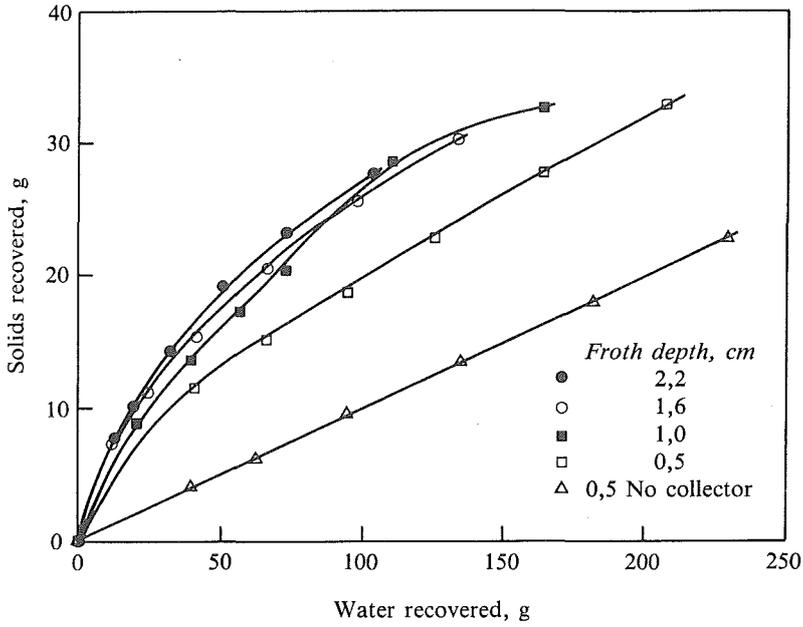


Figure 5 Recovery of solids and water in the presence and absence of collector (gangue: Unisel thickener underflow)

Figure 6 The variation of  $Y_i(t)$  with operating conditions (gangue: Delmas silica sand)

$Y_i(t)$  decreased when the depth of the froth was reduced, which suggests that the ratio of floated material to entrained material decreased under these conditions. (A high value of  $Y_i(t)$  in relation to  $Y_i(t_\infty)$  means that the ratio of floating material to entrained material is high, as shown by equations (2) to (4).) These results are in accordance with observations by Moys (1978), Lynch *et al.* (1981), Laplante *et al.* (1983) and Ross (1988). As was to be expected from the results given in Figure 4, the value of  $Y_i(t)$  in the absence of collector did not change with flotation time. These results suggest that no particles were recovered by true flotation under these conditions, which is in accordance with the assumption on which Method 1 is based.

The values of  $X_i(t_\infty)$ , that describe the differential classification of entrained particles and water at the end of the batch flotation test according to Method 3, are given in Table 3.

Table 3 Variations in the transfer factor  $X_i(t_\infty)$  with different types of gangue material and operating conditions ( $t_\infty = 8$  min).

Initial volume of water in cell, litres	Collector present?	Delmas silica sand	Unisel thickener underflow
2,3	Yes	0,40	0,53
2,4	Yes	0,37	0,42
2,5	Yes	0,35	0,38
2,6	Yes	0,34	0,36
2,6	No	0,28	0,30

The same trends were followed as with  $Y_i(t)$ , i.e. the value of  $X_i(t_\infty)$  increased when the depth of the froth was increased, which shows that the amount of entrained material that was recovered at the end of the batch flotation test increased relative to the amount of water that was recovered when the froth depth was reduced. This probably occurred as a result of the coarse particles being trapped between the bubbles in the froth, while the water drained more freely back to the pulp. For a shallower froth, this effect would be less pronounced, and the ratio of entrained material to water that was recovered in the concentrate would decrease. The value of  $X_i(t_\infty)$  at a froth depth of 0,5 cm was lower in the absence of collector than in the presence of collector, which showed that the decreased stability of the froth in the former case led to a higher drop-out of entrained particles from the froth relative to that of water.

The corresponding results for the Unisel thickener underflow are given in Figure 7. The value of  $Y_i(t)$  after a flotation time of 0,25 minutes was the highest when the froth was the deepest (2,1 cm) and decreased steadily with flotation time. However, at froth depths of 1,5, 0,9 and 0,4 cm, the values of  $Y_i(t)$  decreased steadily over the first minute of flotation, but then flattened out and increased slightly up to a flotation time of 4 minutes. They decreased again and were lower than at 2,1 cm after a flotation time of 8 minutes. The trends at a froth depth of 1,5 cm were slightly less pronounced than those at 0,9 and 0,4 cm respectively.

The same effect was also observed on a synthetic ore consisting of pyritic material from a residue dump and khaki shale that came from the same source as the samples used in this investigation. The reason for the observed effect becomes clear when the mass percentages of the individual particle-size fractions for these flotation tests are inspected. Figures 8 and 9 illustrate the variation in the mass percentages with increasing flotation time of the individual size fractions for froth depths of 0,9 cm, and 0,4 cm respectively in the absence of collector. Figure 8 illustrates that the mass percentages of all the +38  $\mu\text{m}$  fractions decreased during the initial stages of flotation, but, with the exception of the -106+75  $\mu\text{m}$  fraction, which contained the pyrite, increased significantly after a flotation time of 4 minutes. However, when a froth depth of 0,4 cm was used (Figure 9), the increase after a flotation time of 2 minutes was followed by a decrease after flotation for 4 minutes. The increase in the mass percentages suggests that the coarser particles became trapped in the bubble films, while the decrease in the value of  $Y_i(t)$  after the same flotation time shows that the water was still recovered at a faster rate than the solids. It should be noted that the increase in the mass percentages of the coarser particles occurred after flotation times of 8 and 4 minutes at froth depths of 0,9 and 0,4 cm respectively. The increase in the values of  $Y_i(t)$  occurred after flotation times of 4 and 2 minutes, i.e. before the increase in the mass percentages. Therefore, the increase in the values of  $Y_i(t)$  was probably caused by the retarded drainage of entrained particles as the

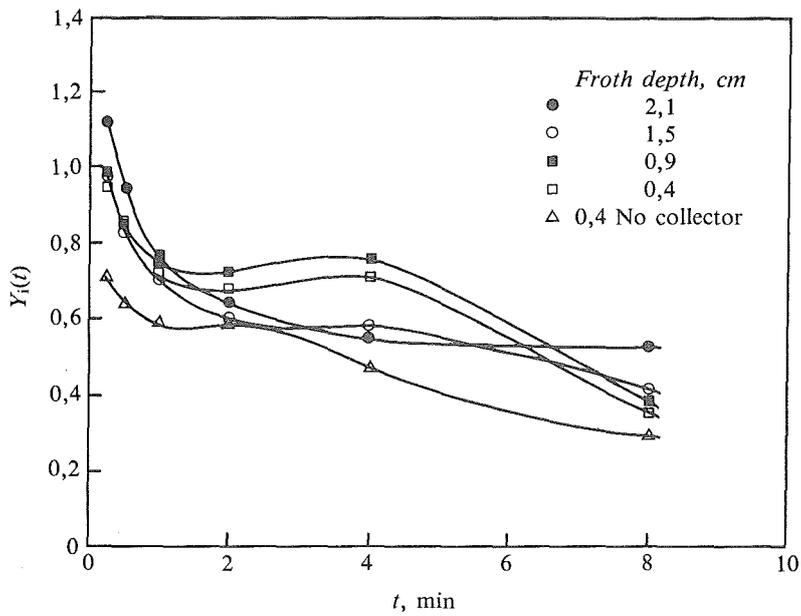


Figure 7 The variation of the parameter  $Y_i(t)$  with operating conditions (gangue: Unisel thickener underflow)

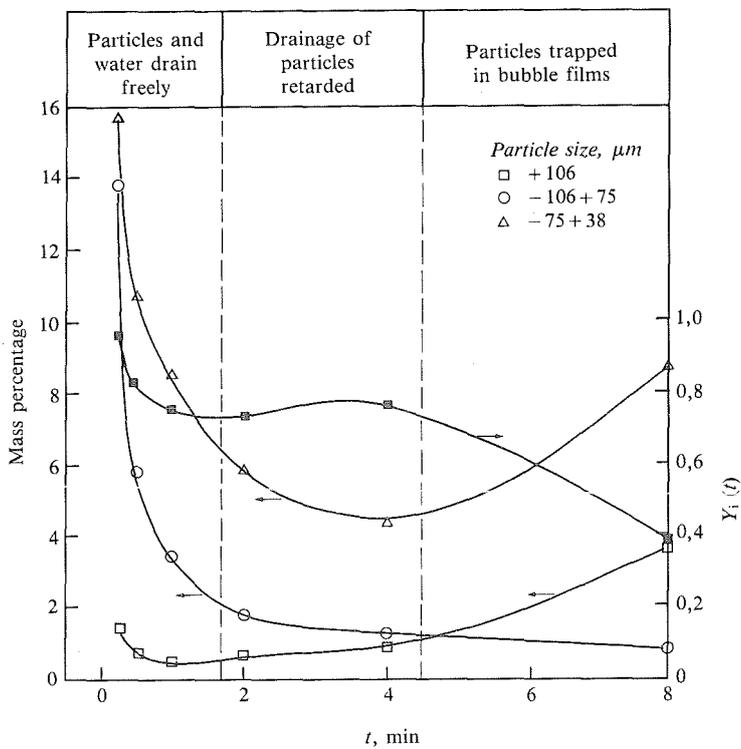


Figure 8 The variation in the mass percentages of particle size fractions with time (gangue: Unisel thickener underflow, froth depth: 0,9 cm)

bubble films grew thinner, while the water could still drain freely back to the pulp, i.e. it was not caused by flotation but by an entrainment effect. The decrease in the mass percentages and the value of  $Y_i(t)$  after a flotation time of 4 minutes at a froth depth of 0,4 cm in the absence of collector was also partly caused by the dropping back of the coarser particles to the pulp as the bubble films became too fragile to support them. These conclusions are substantiated by the brittle nature of the froth towards the end of a batch flotation test (very little solids are recovered, although a substantial amount of water is still obtained).

Table 3 shows that the values of  $X_i(t_\infty)$  increased when the depth of the froth was increased, which is similar to the trends when Delmas silica sand was used as the major gangue component. This increase is also believed to have been caused by the entrapment of the coarse particles in the bubble films, which resulted in an increased ratio of entrained solids to water under these conditions.

Figure 10 gives the calculated amount of solids that were recovered by true flotation and entrainment according to Methods 1, 2 and 3 when the Delmas silica sand was used as the major gangue component. The mass of particles that were floated according to Method 2 was the greatest for the three methods, and those predicted by Methods 1 and 3 were the lowest. Since the total amount of solids that were recovered in each of the methods is the same, the calculated mass of particles that were recovered due to entrainment was in a

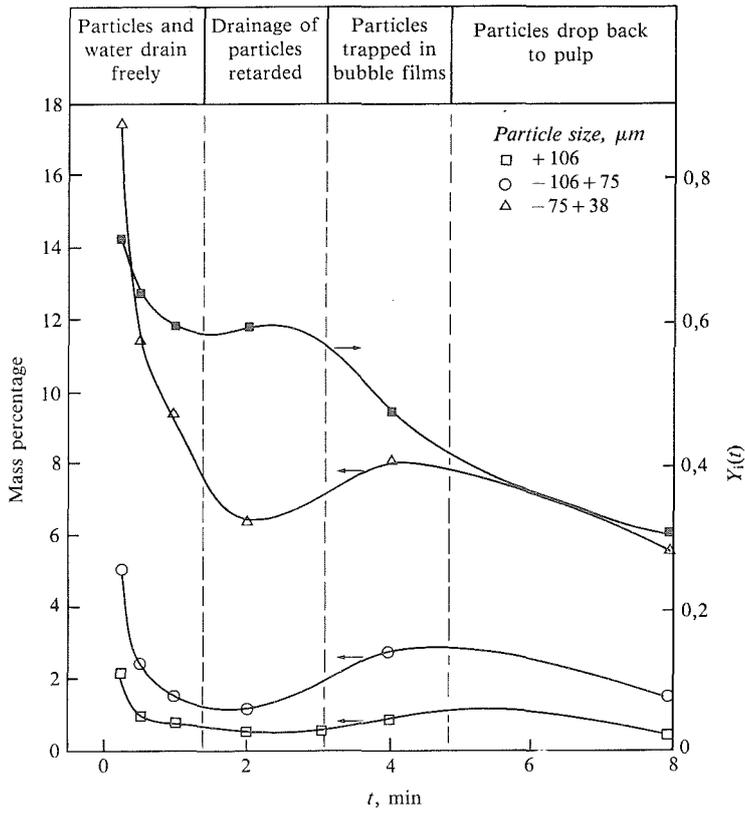


Figure 9 The variation in the mass percentages of particle size fractions with time (gangue: Unisel thickener underflow, froth depth: 0,4 cm, no collector present)

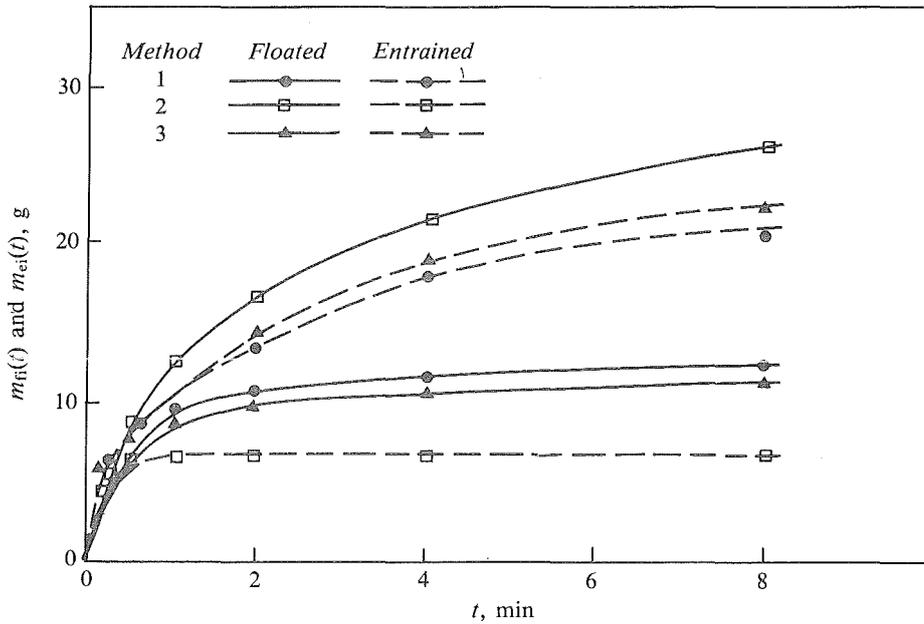


Figure 10 The amount of material recovered by true flotation according to Methods 1 to 3 (gangue: Delmas silica sand)

reversed order. Figure 11 gives the calculated amount of solids that were recovered by true flotation and entrainment when the Unisel thickener underflow was used as the major gangue component in the feed. The three methods predicted the recovery of similar amounts of material by true flotation under these conditions.

#### 4. DISCUSSION

One of the most important findings to emerge from the testwork is that the three methods can yield widely differing results. The application of any specific method should therefore be carried out with great care. It also seems that one or other of the methods may be better suited for the interpretation of batch flotation data under certain operating conditions. Therefore, it is important, if the batch flotation results for a specific set of conditions is to be interpreted correctly, that an analysis should be made of the advantages and disadvantages of the respective methods, and of the assumptions on which they are based.

Method 1 is based on the assumption that, when only a frother is present, no true flotation occurs in the absence of a collector. Ideally, it should therefore be applied under conditions where the frother has no collecting properties and where the feed material is relatively coarse. Trahar (1981) showed that the degree of hydrophobicity required for fine particles to float is much less than that for coarse particles. It is therefore possible that the hydrophobicity

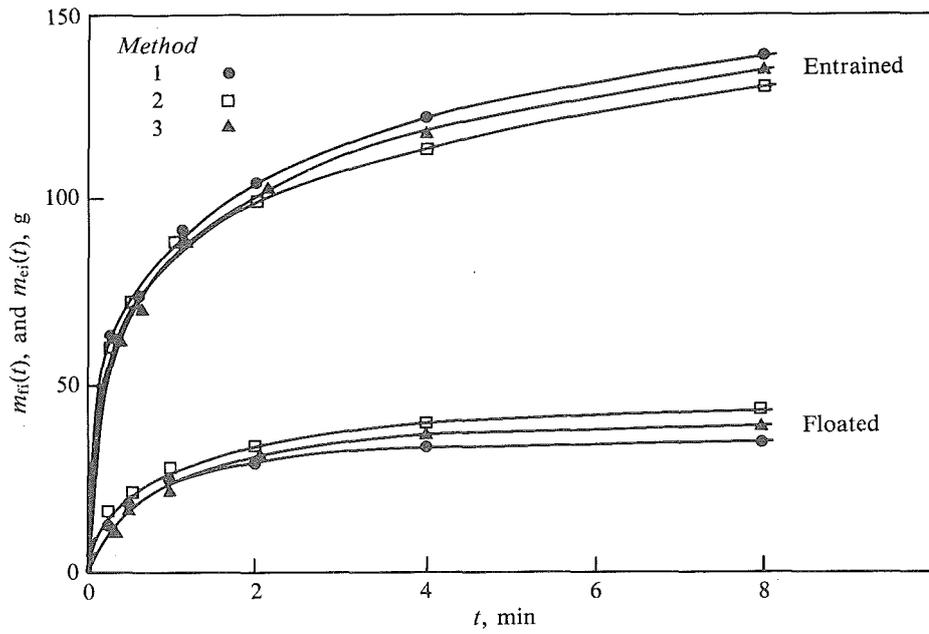


Figure 11 The amount of material recovered by true flotation according to Methods 1 to 3 (gangue: Unisel thickener underflow)

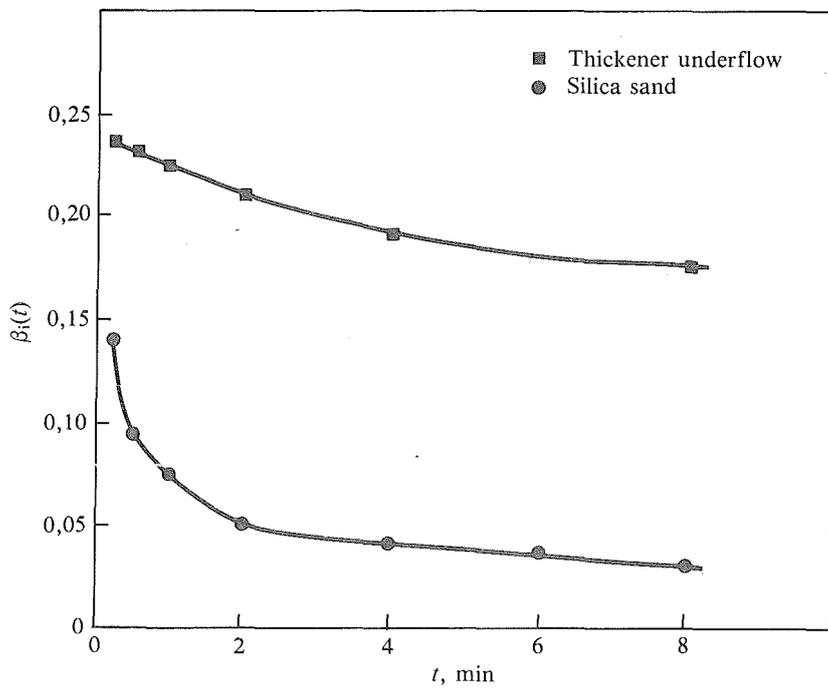


Figure 12 The variation of parameter  $\beta_i(t)$  with time

of fines in the presence of a frother that has collecting properties could, in fact, be high enough for them to be recovered by true flotation. In such a case, the use of Method 1 in the determination of the amount of material that is recovered by true flotation, will give an under-estimated value of  $m_{fi}(t)$  since the amount of entrained solids will be over-estimated in the absence of a collector. This method is not suitable for the interpretation of flotation data if the effect of froth depth on  $m_{fi}(t)$  is to be studied, since almost no froth is normally formed in the absence of a collector. In the present work, for example, a very shallow froth (0,4 cm) had to be used to recover material in the absence of a collector (the initial water volume was 2,6 l). No material could be recovered in the absence of a collector by scraping at initial water volumes of 2,5 litres or lower (this may also occur when low pulp densities are used). This method also has the disadvantage that the amount of entrained material could differ in the presence and in the absence of a collector, since the stability of the froth will be different under such conditions. As was mentioned above, there is evidence (Ross, 1988) that the differential classification of entrained solids and water, and therefore the degree of entrainment, also depends on the characteristics of the froth phase.

The assumption that no true flotation occurs in the absence of a collector was valid when the silica sand was used as the gangue, and therefore the calculated amount of floated material that was obtained by the use of Method 1 can be

assumed to be representative of the true situation. This is further substantiated by the similar amount of floated material that was calculated according to Method 3. The reason for the presumably incorrect prediction of Method 2 is analysed below.

Method 2 is the most time-consuming of the three methods, since it involves a number of batch flotation tests. Since the depth of the froth is varied in order to obtain different ratios of solids to water in the concentrate, errors can arise in the amount of material that is recovered by true flotation if the froth conditions are such that the particles become detached from the surfaces of the bubbles. This can occur if the froth is very brittle, or if it is overloaded with floating particles. When this method is used, it is also very important that the conditioning of the pulp should be carried out accurately, since further errors can be introduced if the valuable particles are not equally hydrophobic during all the batch flotation tests that have to be performed.

Warren (1985) found that the *correlation* between  $R_m$  and  $R_w$ , where  $R_m$  is the recovery of mineral in a given time, and  $R_w$  is the recovery of water in the same time, normally deteriorates with time. The rate of recovery of hydrophobic particles is usually high at the beginning and decreases with an increase in the flotation time. On the other hand, the rate of recovery of water generally remains almost constant throughout a batch flotation test, which means that the *ratio*

$R_m/R_w$  normally decreases towards the end of the test. Therefore, Method 2 should ideally be applied over a flotation time that is just long enough for the recovery of most, but not all, of the easily floatable solids. This means that the choice of a proper time interval is important, and that this interval will depend on the type and fineness of the ore that is floated. For example, Warren used a flotation time of 15 minutes for the flotation of an ultrafine ( $-6 \mu\text{m}$ ) cassiterite ore, and 2 minutes for the flotation of a sample of coal (16 per cent  $-74 \mu\text{m}$ ).

Because of the assumption of a constant ratio  $m_{e_i}(t^*)/m_{e_q}(t^*)$  over the chosen cumulative time interval  $t^*$ , Method 2 is not particularly suitable for use in the study of the rate of true flotation. Significant errors can be made in the calculated amount of entrained material if the value of  $\beta_i(t)$  (where  $t < t^*$ ) decreases significantly with time over the chosen interval, i.e. if too large an interval is chosen. If  $\beta_i(t^*)$  is assumed to be constant over time interval  $t^*$ , the higher values of  $\beta_i(t)$  at  $t < t^*$  are not taken into account in the calculation of  $m_{e_i}(t^*)$ , and its value will therefore be under-estimated. In other words, if  $\beta_i(t^*)$  is under-estimated, the value of  $m_{e_i}(t^*)$  will also be under-estimated, since it is based on the same water recovery  $m_{e_q}(t^*)$ . Consequently, the value of  $m_{f_i}(t^*)$ , the total mass of particles that are recovered by true flotation after time  $t^*$ , will be over-estimated. This is presumed to have occurred when the relatively coarse silica was used as the major gangue material, since the values of  $\beta_i(t)$  decreased

significantly with time over the first 2 minutes of flotation (Figure 12). The under-estimation of  $\beta_i(t)$  and  $m_{e_i}(t)$  will therefore become progressively larger with an increase in flotation time, resulting in an over-estimated value of  $m_{f_i}(t)$ .

However, the value of  $\beta_i(t^*)$  will remain fairly constant over a large time interval when fine material is floated (such was the case when Unisel thickener underflow was used as the major gangue component), as illustrated in Figure 12. Under these conditions, the calculated amount of material that is recovered by true flotation, according to Method 2, will be predicted more accurately. As illustrated in Figure 11, this observation is substantiated by the similar amount of floated material that was predicted by Methods 1, 2, and 3 when the Unisel thickener underflow was used as the major gangue component. The slightly larger values of  $m_{f_i}(t)$  are presumed to have been caused by the slight decrease in the value of  $\beta_i(t)$  with an increase in flotation time.

Method 3 is the least time-consuming method, since it involves only one flotation test. It is therefore the most suitable for use in the investigation of the effect of froth depth on the amount of material that is recovered by true flotation. Since the changes in the characteristics of the froth and the composition of the pulp with flotation time are taken into consideration, it can be applied over any flotation time. For example, if a large amount of solids is recovered by true flotation and/or entrainment, the corre-

sponding drop in the solids content of the pulp is taken into account, which results in a decreased possibility for the entrainment of particles. As can be seen from Figures 10 and 11, the predicted amount of floated material was similar to that predicted by Method 1 for both the Delmas silica sand and the Unisel thickener underflow, which suggests that this method is of acceptable accuracy.

It is assumed in Method 3 that the pulp is perfectly mixed. This assumption may not be true for very coarse feeds and for low pulp densities, and the ratio  $C_{\tau q}(t)/C_{\tau i}(t)$  at the top of the pulp may be higher than was calculated. If this ratio has a marked effect on the entrainment of particles at the top of the pulp, i.e. if the composition of the pulp at the pulp-froth interface determines the amount and nature of species that is entrained, the values of  $X_i(t)$ , and hence  $m_{e i}(t)$ , may be under-estimated. Therefore, the values of  $m_{f i}(t)$  may be over-estimated when they are calculated from the relationship  $m_{f i}(t) = m_{t i}(t) - m_{e i}(t)$ .

## 5. CONCLUSIONS

A comparison of three different methods for the determination of the amount of material that is recovered by true flotation and entrainment during batch flotation tests shows that the application of any particular method should be carried out with care since, under different operating conditions, the calculated amount of material that is recovered by true flotation can differ significantly for the respective

methods.

The investigation showed that Method 1 should be applied when the frother has no collecting properties and when the feed material is fairly coarse. However, it is unsuitable for the investigation of the effect of froth depth on the mass of particles that are recovered by true flotation, since very little froth is normally formed in the absence of collector. Ideally, Method 2 should be applied only over a flotation interval that is just long enough for the recovery of most, but not all, of the easily floatable solids. The conditions should be such that a good correlation exists between the recovery of the mineral,  $R_m$ , and the recovery of the water,  $R_w$ , over the total flotation interval  $t^*$  that is studied. This method is also not suited for the study of the rate of true flotation because of a possible decrease in the value of  $\beta_i(t)$  with an increase in flotation time when coarse particles are floated. It is also the most time-consuming method. Method 3 is the most suitable for the study of the effect of froth depth on the rate of true flotation, and is also the least time-consuming of the three methods. However, it should be applied at a pulp density that is sufficient for good mixing of the pulp phase.

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