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DEPARTMENT OF  
ENERGY, MINES AND RESOURCES  
MINES BRANCH  
OTTAWA

*INVESTIGATIONS ON FLOTATION  
OF COPPER-NICKEL ORE*

W. R. HONEYWELL AND F. J. KELLY

EXTRACTION METALLURGY DIVISION

AUGUST 1970



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Ottawa, 1970

Mines Branch Technical Bulletin TB 128

INVESTIGATIONS ON FLOTATION  
OF COPPER-NICKEL ORE

by

W.R. Honeywell\* and F.J. Kelly\*

SUMMARY

An investigation was carried out on a copper-nickel ore to develop flotation methods to produce a bulk copper-nickel concentrate. The effects of grind, pH, and collector reagent additions, on recovery, grade, kinetic flotation rate and the probability that mineral particles will float, were determined. All correlations were done by regression analysis techniques.

The test work yielded significant empirical models that relate the nickel metallurgy of the system to changes in operating variable levels. With the exception of recovery, no significant correlation between the operating variables and the copper responses of the system was established.

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Direction des mines  
Bulletin technique TB 128

ÉTUDES SUR LA FLOTTATION  
DU MINERAI DE CUIVRE-NICKEL

par

W.R. Honeywell\* et F.J. Kelly\*

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RÉSUMÉ

Les auteurs ont étudié un minerai de cuivre-nickel en vue de mettre au point des méthodes de flottation permettant de produire un concentré brut de cuivre-nickel. Ils ont étudié les effets de la granulométrie, du pH et d'additions diverses d'agents collecteurs sur le taux de récupération, la qualité du produit, la vitesse cinétique de flottation et la probabilité que les particules minérales flotteront. Toutes les corrélations ont été établies au moyen des techniques d'analyse par régression.

Les essais ont permis d'établir des modèles empiriques valables qui définissent les relations entre la métallurgie du nickel de ce système et la modification des variables opérationnelles. Mis à part le taux de récupération, aucune corrélation significative n'a pu être établie entre les variables opérationnelles et les réactions du cuivre au procédé employé.

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## INTRODUCTION

A general investigation of the flotation properties of Cu-Ni-Fe sulphide ores was initiated, based on the possibility that if a successful hydrometallurgical process for the treatment of these ores were developed it might then be possible to treat a lower-grade bulk flotation concentrate than can be treated by smelting. In the work reported here, an investigation was done on a copper-nickel ore from the Werner Lake mine of Consolidated Canadian Faraday, Limited, which is located north-east of Kenora, Ontario. The object of the work was to develop flotation methods to produce as high a recovery of the metals as possible, in a bulk copper-nickel concentrate, although some work was done to compare the results of bulk flotation with those of selective flotation. Experiments were designed to study the effects of grind, pH, and reagent additions on recovery, grade, kinetic <sup>(1)</sup> flotation rate, and the probability <sup>(2)</sup> that mineral particles will float in a bulk concentrate.

## SAMPLES AND MINERALOGY

Two samples of mine ore from the Werner Lake mine, in northwestern Ontario, of Consolidated Canadian Faraday, Limited, were received in November 1968. The first sample analyzed 1.11% nickel, 0.51% copper, 1.87% sulphur, and 16.1% iron. The second sample was slightly lower in grade, analyzing 0.90% nickel, 0.36% copper, and 13.5% iron.

A mineralogical examination of the ore by Mr. M.R. Hughson of the Extraction Metallurgy Division showed that the sample material consisted of a dark-coloured, medium-grained rock which contained finely disseminated metallic grains. The main rock-forming minerals were serpentine, talc, amphibole, and biotite, with minor amounts of quartz and feldspars. Pentlandite and chalcopyrite were the main ore minerals and they occurred in complex intergrowths with pyrrhotite, magnetite, and pyrite. Free metallic grains were not common. A large proportion of the pentlandite and chalcopyrite grains exceeded 10 mesh in size.

#### PROCEDURE

In all of the work reported in this paper, a Fagergren laboratory flotation machine, equipped with a glass cell, was used. Preliminary to the main body of test work, some exploratory tests were done to indicate what type and amount of flotation reagents, as well as other flotation conditions such as grind and pH, should be studied in subsequent, more detailed work. These preliminary studies involved both bulk and selective flotation tests.

The first series of tests done to study bulk flotation investigated the effects of the grind, and of the amounts added of Cyanamid reagents 301 and R-238 and Dow reagent Z-200, on bulk flotation results. An experimental design in which the four variables were run at two levels each (Table 1) was used for this study. To provide a test



TABLE 1

Experimental Conditions to Determine Significant Variables on Bulk Flotation of Nickel and Copper

Test No.	X <sub>1</sub> , Grind, %-200M	X <sub>2</sub> , 301 Xanthate, lb/ton	X <sub>3</sub> , Z-200, lb/ton	X <sub>4</sub> , R-238, lb/ton	Remarks
1	60	0.03	0.034	nil	
2	60	0.03	0.034	0.04	
3	60	0.10	0.102	nil	
4	60	0.10	0.102	0.04	
5	60	0.10	0.102	0.04	Duplicate of Test 4
6	89	0.03	0.034	nil	
7	89	0.03	0.034	0.04	
8	89	0.03	0.102	nil	
9	89	0.03	0.102	nil	Duplicate of Test 8
10	89	0.03	0.102	0.04	
11	89	0.10	0.034	nil	
12	89	0.10	0.034	0.04	
13	89	0.10	0.102	nil	
14	89	0.10	0.102	0.04	
15	89	0.10	0.102	0.04	Duplicate of Test 14
16	60	0.03	0.102	nil	
17	60	0.03	0.102	0.04	
18	60	0.10	0.034	nil	
19	60	0.10	0.034	nil	Duplicate of Test 18
20	60	0.10	0.034	0.04	

for experimental error, four duplicate tests were run. In all of these tests the pulp density of the flotation feed was 32% solids.

Based on the results of the regression analysis of the data from the series outlined in Table 1, a second experimental design, consisting of 17 bulk flotation tests, was run. In all of the tests in the second series the grind was about 80% minus 200 mesh, the amount of 301 Xanthate added was 0.06 lb per ton of ore, and the pulp density was 32% solids. The effects on the bulk flotation of pH and the amount of Z-200 and R-238 added were investigated by an experimental design in which the pH was run at three levels and the reagents at two levels (Table 2). Four duplicate tests were run to provide a test for experimental error.

In all of the bulk flotation tests, the flotation concentrate was collected in 30-second increments over the total flotation period. Each incremental sample was analyzed for copper and nickel and the recovery in each was calculated. From these data, flotation rates and probabilities of flotation were obtained.

## RESULTS

In the preliminary test work, several flotation reagents were found to be equally promising for the recovery of the copper and nickel sulphides from the Werner Lake ore, either as a bulk concentrate or as separate concentrates. The reagents used were

TABLE 2

Experimental Conditions to Determine the Effects of pH, and Amounts of Z-200 and R-238, on Bulk Flotation

Test No.	X <sub>1</sub> pH	X <sub>2</sub> Z-200, lb/ton	X <sub>3</sub> R-238, lb/ton	Remarks
1	7	0.034	0.02	
2	7	0.034	0.06	
3	10	0.034	0.02	
4	10	0.034	0.02	Duplicate of Test 3
5	10	0.034	0.06	
6	7	0.102	0.02	
7	7	0.102	0.06	
8	7	0.102	0.06	Duplicate of Test 7
9	10	0.102	0.02	
10	10	0.102	0.06	
11	8.5	0.034	0.02	
12	8.5	0.034	0.06	
13	8.5	0.102	0.02	
14	8.5	0.102	0.02	Duplicate of Test 13
15	8.5	0.102	0.06	
16	8.5	0.068	0.04	
17	8.5	0.068	0.04	Duplicate of Test 16



Cyanamid R-208, Cyanamid R-238, Dow Z-200, Cyanamid Xanthate 325, and Cyanamid Xanthate 301. All of these reagents were added in amounts ranging from about 0.03 to 0.15 lb/ton of ore.

In selective flotation tests, about 85% of the copper and 5% of the nickel reported in the copper concentrate which analyzed 18.7% Cu. The nickel concentrate contained 75% of the nickel and 11% of the copper, and analyzed 5.6% Ni. This degree of selectivity was not considered to be satisfactory.

In bulk flotation tests the indications were that 90% or more of the copper, and up to 80% of the nickel, could be recovered in a bulk concentrate analyzing 4 to 5% Cu and about 8% Ni. On the basis of these preliminary results it was decided to devote the main part of the work to a study of bulk flotation. It was also decided to use Cyanamid reagents R-238 and 301 and Dow reagent Z-200 in the main flotation study, as these appeared to give the best results in the preliminary work.

The responses obtained in the first series of tests to investigate bulk flotation are shown in Table 3, and were correlated with the test conditions (Table 1) by determining first-order linear relationships by multi-variable regression methods. The regression showed that the variables Z-200 and R-238 were the most significant and that the grind and the reagent concentration of 301 Xanthate were not significant within the range investigated.



TABLE 3

## Regression Input Data and Responses - First Series of Tests

Test No.	Variables				Responses				Remarks
	X <sub>1</sub> Grind, %-200M	X <sub>2</sub> 301 Xanthate, lb/ton	X <sub>3</sub> Z-200, lb/ton	X <sub>4</sub> R-238, lb/ton	Copper		Nickel		
					Conc. %	Recovery %	Conc. %	Recovery %	
1	60	0.03	0.034	nil	4.96	87.9	6.67	44.7	
2	60	0.03	0.034	0.04	3.41	90.4	6.60	70.1	
3	60	0.10	0.102	nil	3.18	91.9	5.93	72.6	
4	60	0.10	0.102	0.04	2.32	93.0	4.08	77.3	
5	60	0.10	0.102	0.04	2.54	88.5	4.43	65.5	Duplicate of Test 4
6	89	0.03	0.034	nil	4.07	92.3	5.69	52.0	
7	89	0.03	0.034	0.04	2.75	92.0	5.49	70.6	
8	89	0.03	0.102	nil	2.38	92.5	5.04	73.1	
9	89	0.03	0.102	nil	2.20	88.2	4.01	64.9	Duplicate of Test 8
10	89	0.03	0.102	0.04	2.16	95.3	4.98	80.3	
11	89	0.10	0.034	nil	4.12	88.8	7.27	56.9	
12	89	0.10	0.034	0.04	3.40	92.4	7.04	69.6	
13	89	0.10	0.102	nil	2.38	93.1	5.50	78.2	
14	89	0.10	0.102	0.04	2.03	94.0	4.65	79.9	
15	89	0.10	0.102	0.04	2.04	91.2	3.97	70.0	Duplicate of Test 14
16	60	0.03	0.102	nil	2.03	92.7	4.42	76.7	
17	60	0.03	0.102	0.04	2.45	92.7	5.10	74.8	
18	60	0.10	0.034	nil	3.97	89.7	7.67	62.2	
19	60	0.10	0.034	nil	4.88	82.9	6.90	48.8	Duplicate of Test 18
20	60	0.10	0.034	0.04	3.33	92.9	7.01	76.9	

The responses obtained in the second series of tests to further investigate bulk flotation are shown in Table 4. The method used to obtain the m, k and p values shown under headings "kinetic" and "probability" in Table 4 is demonstrated in the following detailed determination of these values as they apply to Tests 7 and 10, Table 2. The results obtained in these two tests are given in Table 5 and Figures 1A and 1B. The Y-axis on both figures is the natural logarithm of the difference of one and the fractional cumulative recovery. The X-axis on Figure 1A is the natural logarithm of time, and on 1B the number of cells. For small laboratory batch flotation tests, where the weight of concentrate removed in a given time interval decreases with time, the number of cells in an equivalent bank of cells is approximately equal to a geometric time series <sup>(1)</sup> of the intervals used in the test. In other words, the mass fraction of metal that would remain in cells 1, 2, 3, and 4 of a bank of 4 would be roughly equivalent to that present in the batch cell in this work at 0.5, 1, 2, and 4 minutes of flotation time.

The straight-line fits shown on Figures 1A and 1B were determined by the method of least squares. It can be seen that the plotted data, particularly those for nickel, are close to straight-line functions for the first four minutes of flotation. The first-order kinetic flotation model<sup>(1)</sup> plotted on Figure 1A has the form:

TABLE 4

## Regression Input Data and Responses - Second Series of Tests

Test No.	Variables			Responses												Remarks
	pH	Z-200 (lb/ton)	R-238 (lb/ton)	Copper						Nickel						
				Grade (%)	Recovery (%)	Kinetic		Probability		Grade (%)	Recovery (%)	Kinetic		Probability		
						M	K	M	P			M	K	M	P	
	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	Y <sub>1</sub>	Y <sub>2</sub>	Y <sub>3</sub>	Y <sub>4</sub>	Y <sub>5</sub>	Y <sub>6</sub>	Y <sub>1</sub>	Y <sub>2</sub>	Y <sub>3</sub>	Y <sub>4</sub>	Y <sub>5</sub>	Y <sub>6</sub>	
1	7	0.034	0.02	5.07	84.5	0.363	-0.500	0.742	0.297	4.85	33.0	0.904	-0.127	1.068	0.082	
2	7	0.034	0.06	3.76	87.8	0.266	-0.472	0.524	0.283	5.46	51.7	0.773	-0.228	1.051	0.143	
3	10	0.034	0.02	4.03	87.5	0.312	-0.561	0.692	0.324	6.89	61.1	0.718	-0.348	1.148	0.209	
4	10	0.034	0.02	4.21	86.8	0.326	-0.592	0.761	0.339	7.65	60.4	0.697	-0.342	1.113	0.207	Duplicate of Test 3
5	10	0.034	0.06	3.13	89.5	0.253	-0.537	0.541	0.313	5.63	70.6	0.544	-0.380	0.929	0.232	
6	7	0.102	0.02	2.42	89.5	0.270	-0.553	0.582	0.320	4.04	59.9	0.755	-0.264	1.074	0.165	
7	7	0.102	0.06	2.57	89.8	0.247	-0.528	0.532	0.314	4.14	64.6	0.694	-0.285	1.033	0.181	
8	7	0.102	0.06	2.34	90.1	0.270	-0.583	0.630	0.340	3.99	61.0	0.719	-0.279	1.058	0.176	Duplicate of Test 7
9	10	0.102	0.02	2.67	89.6	0.243	-0.513	0.511	0.306	5.01	69.4	0.607	-0.369	1.015	0.226	
10	10	0.102	0.06	2.40	89.4	0.234	-0.460	0.455	0.278	4.72	71.9	0.547	-0.365	0.912	0.223	
11	8.5	0.034	0.02	4.09	84.5	0.364	-0.498	0.737	0.294	6.02	50.9	0.754	-0.238	1.046	0.151	
12	8.5	0.034	0.06	3.14	87.6	0.303	-0.516	0.641	0.307	4.95	58.8	0.688	-0.282	1.014	0.176	
13	8.5	0.102	0.02	2.81	88.2	0.296	-0.557	0.670	0.329	4.45	63.3	0.664	-0.302	1.008	0.188	
14	8.5	0.102	0.02	2.55	88.7	0.271	-0.508	0.564	0.303	4.35	65.4	0.640	-0.304	0.976	0.190	Duplicate of Test 13
15	8.5	0.102	0.06	1.88	90.9	0.269	-0.626	0.661	0.358	3.65	68.7	0.591	-0.341	0.953	0.211	
16	8.5	0.068	0.04	2.64	88.6	0.282	-0.519	0.596	0.307	4.54	65.2	0.659	-0.307	1.008	0.191	
17	8.5	0.068	0.04	2.55	89.1	0.291	-0.570	0.667	0.334	4.20	65.2	0.626	-0.313	0.967	0.194	Duplicate of Test 16



TABLE 5

Detailed Flotation Results for Tests 7 and 10 of Table 2

Time (min)	Test No. 7							Test No. 10						
	pH = 7; 0.102 lb/t Z-200; 0.06 lb/t R-238							pH = 10; 0.102 lb/t Z-200; 0.06 lb/t R-238						
	Conc Wt (%)	Conc Cu Analysis (%)	Cu Recovery in Conc (%)	Cu Cum Recovery (%)	Conc Ni Analysis (%)	Ni Recovery in Conc (%)	Ni Cum Recovery (%)	Conc Wt (%)	Conc Cu Analysis (%)	Cu Recovery in Conc (%)	Cu Cum Recovery (%)	Conc Ni Analysis (%)	Ni Recovery in Conc (%)	Ni Cum Recovery (%)
0.5	2.34	9.63	60.2	60.2	5.75	16.1	16.1	3.02	8.08	64.9	64.9	8.63	28.4	28.4
1.0	1.61	3.89	16.9	77.1	7.03	13.5	29.6	1.73	2.80	12.9	77.8	8.93	16.8	45.2
1.5	1.25	1.33	4.5	81.6	5.74	8.6	38.2	1.22	1.22	4.0	81.8	6.39	8.5	53.7
2.0	0.99	0.88	2.4	84.0	4.47	5.2	43.4	1.01	0.79	2.1	83.9	4.25	4.7	58.4
2.5	0.69	0.65	1.1	85.1	3.39	2.7	46.1	1.05	0.39	1.1	85.0	2.61	2.9	61.3
3.0	0.77	0.44	0.8	85.9	3.30	3.0	49.1	0.96	0.35	0.8	85.8	2.09	2.2	63.5
3.5	0.71	0.36	0.8	86.7	2.67	2.3	51.4	0.74	0.33	0.5	86.3	1.90	1.5	65.0
4.0	0.75	0.33	0.5	87.2	2.39	2.2	53.6	0.78	0.24	0.5	86.8	1.45	1.2	66.2
4.5	0.79	0.29	0.5	87.7	2.12	2.0	55.6	0.80	0.21	0.5	87.3	1.25	1.1	67.3
5.0	0.90	0.21	0.5	88.2	1.69	1.8	57.4	0.75	0.20	0.5	87.8	1.21	1.0	68.3
5.5	0.65	0.30	0.5	88.7	2.61	2.0	59.4	0.35	0.47	0.5	88.3	2.40	0.9	69.2
6.0	0.58	0.28	0.5	89.2	3.01	2.0	61.4	0.37	0.41	0.5	88.8	2.21	0.9	70.1
6.5	0.46	0.28	0.3	89.5	2.91	1.6	63.0	0.55	0.26	0.3	89.1	1.64	1.0	71.1
7.0	0.59	0.22	0.3	89.8	2.17	1.6	64.6	0.65	0.20	0.3	89.4	1.25	0.8	71.9
Conc	13.08	2.57	89.8		4.14	64.6		13.98	2.40	89.4		4.72	71.9	
Tailings	86.92	0.044	10.2		0.34	35.4		86.02	0.046	10.6		0.30	28.1	
Head	100.00	0.37	100.0		0.84	100.0		100.00	0.38	100.0		0.92	100.0	

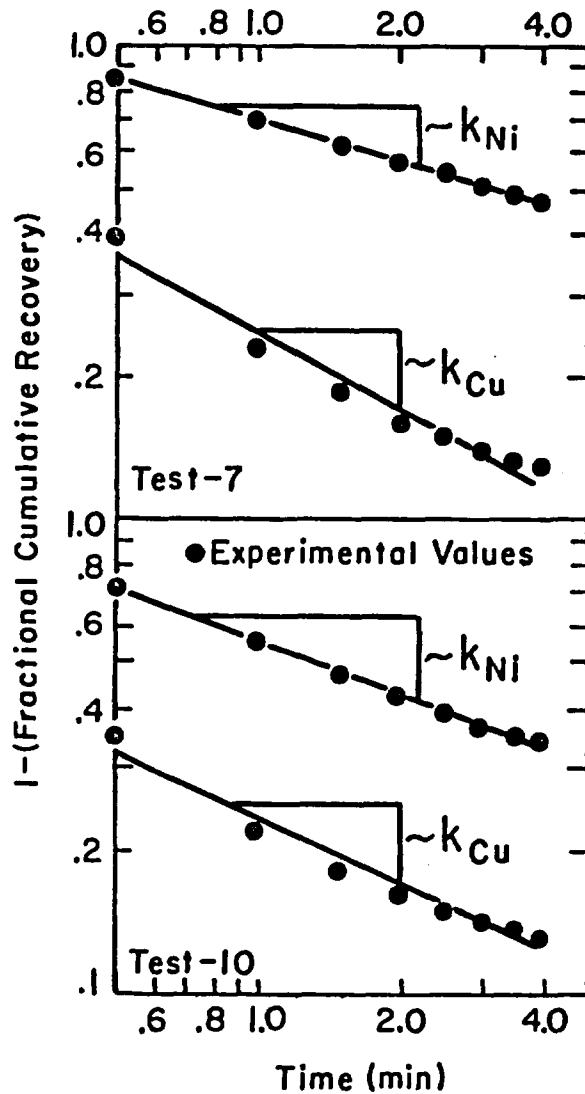


Figure 1A: Mineral Flotation  
Rate  $K/\text{min} = \frac{\ln(1-\text{FCR})}{\ln(\text{Time})}$

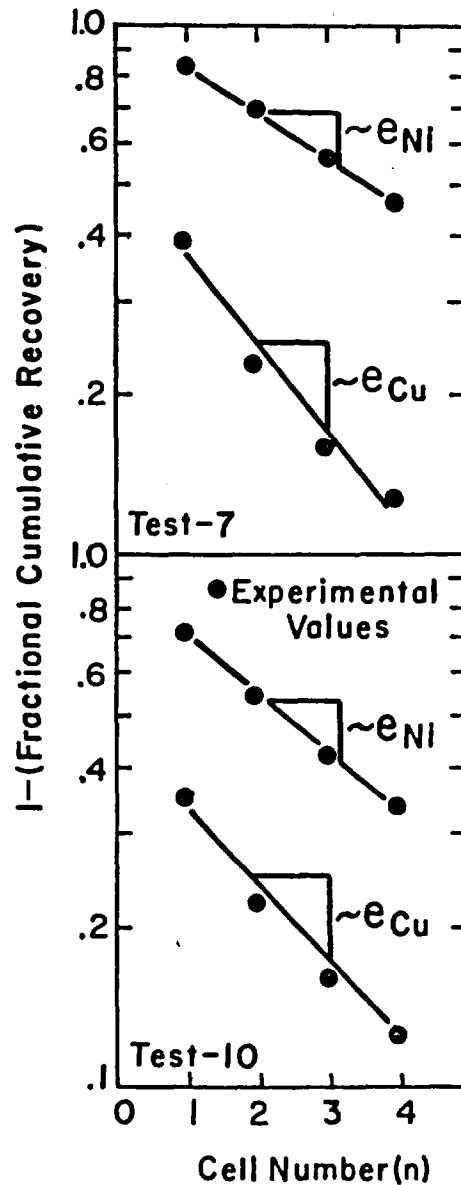


Figure 1B: Probability of Mineral Flotation  
$$P = 1 - e^{-\left(\frac{\ln(1-\text{FCR})}{\text{Cell No.}}\right)}$$

FCR: Fractional Cumulative Recovery

$$R = 1 - me^{klnt} \quad (1)$$

where R = the fractional recovery of the mineral species at time t,  
 m = the value of the plotted line at X equal to 1 min which  
 in logarithmic co-ordinates is the value of the intercept  
 on the vertical axis at X = 0 because  $\ln(1)=0$ ,  
 k = the kinetic flotation rate constant (mass/unit time),  
 t = the natural logarithm of time (min), and  
 e = base of natural logarithm = 2.71828.

The flotation model based on the probability method (2) and  
 plotted on Figure 1B is

$$R = 1 - m(1-P)^n \quad (2)$$

where R has the same meaning as in Equation 1,

m = the value of the intercept at X = 0,

P = the probability that a fractional portion of a mineral  
 species will float, and

n = the number of cells.

The responses ( $Y_1$  to  $Y_6$ ) for both copper and nickel  
 were correlated with the variables ( $X_1$  to  $X_3$ ) of Table 4 by a  
 multi-variable regression technique to determine first-order  
 linear equations. The resulting equations were as follows:

a) Copper

$$\begin{aligned} \text{Conc-Cu (\%)} &= 5.15 - 20.7 \text{ (Z-200 lb/T)} \\ &\quad - 16.1 \text{ (R-238 lb/T)} \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Recovery-Cu (\%)} &= 71.8 + 1.2 \text{ (pH)} \\ &\quad + 167 \text{ (Z-200 lb/T)} + 91.8 \text{ (R-238 lb/T)} \\ &\quad - 12.1 \text{ (pH) (Z-200 lb/T)} \\ &\quad - 646 \text{ (Z-200 lb/T) (R-238 lb/T)} \end{aligned} \quad (4)$$

b) Nickel

$$\begin{aligned} \text{Conc-Ni } (\%) &= 1.03 (\text{pH}) + 93.5 (\text{R-238 lb/T}) \\ &\quad -2.48 (\text{pH}) (\text{Z-200 lb/T}) \\ &\quad -12.6 (\text{pH}) (\text{R-238 lb/T}) -1.89 \end{aligned} \quad (5)$$

$$\begin{aligned} \text{Recovery-Ni } (\%) &= 10.1 (\text{pH}) + 874 (\text{Z-200 lb/T}) \\ &\quad + 414 (\text{R-238 lb/T}) -67.3 (\text{pH}) (\text{Z-200 lb/T}) \\ &\quad -3260 (\text{Z-200 lb/T}) (\text{R-238 lb/T}) -53 \end{aligned} \quad (6)$$

Nickel Kinetic Parameters

$$\begin{aligned} m &= 1.28 - 0.0432 (\text{pH}) - 2.19 (\text{Z-200 lb/T}) \\ &\quad -0.431 (\text{pH}) (\text{R-238 lb/T}) \\ &\quad +22.2 (\text{Z-200 lb/T}) (\text{R-238 lb/T}) \end{aligned} \quad (7)$$

$$\begin{aligned} K_{\text{Ni}} (\text{min}^{-1}) &= 0.603 - 0.09 (\text{pH}) - 5.02 (\text{Z-200 lb/T}) \\ &\quad -4.9 (\text{R-238 lb/T}) + 0.431 (\text{pH}) (\text{Z-200 lb/T}) \\ &\quad +0.34 (\text{pH}) (\text{R-238 lb/T}) \\ &\quad +15.4 (\text{Z-200 lb/T}) (\text{R-238 lb/T}) \end{aligned} \quad (8)$$

Nickel Probability Parameters

$$\begin{aligned} m &= 0.885 + 0.037 (\text{pH}) + 6.29 (\text{R-238 lb/T}) \\ &\quad -0.19 (\text{pH}) (\text{Z-200 lb/T}) -1.12 (\text{pH}) (\text{R-238 lb/T}) \\ &\quad +20.8 (\text{Z-200 lb/T}) (\text{R-238 lb/T}) \end{aligned} \quad (9)$$

$$\begin{aligned} P_{\text{Ni}} &= 0.0527 (\text{pH}) + 3.03 (\text{Z-200 lb/T}) + 2.97 (\text{R-238 lb/T}) \\ &\quad -0.257 (\text{pH}) (\text{Z-200 lb/T}) -0.203 (\text{pH}) (\text{R-238 lb/T}) \\ &\quad -9.53 (\text{Z-200 lb/T}) (\text{R-238 lb/T}) -0.346 \end{aligned} \quad (10)$$

Regarding the regression equations relevant to copper, Equations 3 and 4, in which Cu grade and recovery are the responses, explain 80 and 88% of the observed variation in their respective responses. Equation 3 shows a significant lack of fit and therefore can only be used for the information it imparts about the system. Equation 4 is significant at a confidence level of 95% and can be used for predictive purposes.

When the calculated parameters for the copper and nickel kinetic models ( $m$ ,  $k$  and  $p$  in Table 4) were substituted in Equations 1 and 2, the models accounted for >95% of the observed variations in metal recovery with flotation time. On the other hand, no significant statistical correlations, even at a confidence level of 75%, could be found that would explain the variation between the copper kinetic and probability responses and the operating variables.

The derived nickel relationships (Equations 5 to 10) were statistically significant at the 95% confidence level. Percentages of the observed response variation explained by Equations 5 to 10 are 87, 94, 92, 97, 81, and 97% respectively. Consequently, Equations 5 to 10 can be used to predict responses for all levels of the operating variables within the ranges investigated.

An inspection of Equation 3 shows that the copper analysis of the flotation concentrate decreases as the amounts of Z-200 and R-238 are increased, while pH and the interactive effects between these variables have no effect on this response. The nickel analysis given by Equation 5 increases with the pH and the amount of R-238, but the interactive effects between pH and Z-200 and R-238 will decrease the calculated nickel analysis

as the values of these three variables increase. The copper and nickel calculated from Equations 4 and 6 will increase with increases in the values of the three variables investigated, but will decrease with increasing values of interactive terms.

The kinetic nickel flotation rate, as shown by Equation 8, decreases with increasing pH, Z-200, and R-238. The interactions between all of these variables act in the opposite direction. Equation 10 shows that the probability of nickel flotation increases with increase in pH, Z-200 and R-238 and decreases with increases in the values of the interactive terms.

The relative effect that each of the variables, and each of the interactions between variables, has on the predicted responses of Equations 3 to 10 is shown in Table 6. In excess of 70% of the observed response variation in Equations 3, 4, 5, 6, 8, and 10 (Table 6) is attributable to changes in the levels of the operating variables listed in columns 1, 2 and 3. This means that increases in pH, Z-200, and R-238 levels will upgrade the concentrate with respect to both nickel and copper (Equations 3 and 5); will increase the recovery of nickel and maintain recovery of copper (Equations 4 and 6); and will decrease the flotation time required to recover the nickel.

TABLE 6

Effect of Variables on Responses

Eq. No.	Responses	In Decreasing Order of Magnitude*					
		1	2	3	4	5	6
3	Conc-Cu	-(Z-200)	-(R-238)				
4	Recov-Cu	(Z-200)	-(pH) (Z-200)	(R-238)	-(Z-200) (R-238)	(pH)	
5	Conc-Ni	(pH)	(R-238)	-(pH) (R-238)	-(pH) (Z-200)		
6	Recov-Ni	(Z-200)	-(pH) (Z-200)	(pH)	-(Z-200) (R-238)	(R-238)	
7	<sup>m</sup> Kni	-(pH) (R-238)	-(pH)	-(Z-200)	(Z-200) (R-238)		
8	Kni	-(pH)	(pH) (Z-200)	-(Z-200)	(pH) (R-238)	-(R-238)	(Z-200) (R-238)
9	<sup>m</sup> Pni	-(pH) (R-238)	(R-238)	-(pH) (Z-200)	(Z-200) (R-238)	(pH)	
10	Pni	(pH)	-(pH) (Z-200)	(Z-200)	-(pH) (R-238)	(R-238)	-(Z-200) (R-238)

\*Note: If a variable does not appear, it is considered to have had little or no effect on a response within the ranges investigated; this does not, however, imply that the variable should be deleted from the process.



Two tests were run to verify Equations 3, 4, 5, and

6. The results are given in Table 7.

It will be noted from Table 7 that all of the measured responses except two fell within the predicted 95% confidence intervals. The two values outside these limits were slightly above the upper confidence level.

#### DISCUSSION AND CONCLUSIONS

Both the probability <sup>(1)</sup> and kinetic <sup>(2)</sup> methods of mathematically expressing the recovery of a mineral species in a flotation process have been applied in this paper. The main objection in the past to the probability model has been against the simplifying assumption of a constant probability of floating a mineral species in every cell of a bank of cells, regardless of changes in pulp feed rate and/or mineral content of the ore. However, recent work <sup>(3,4)</sup> done in a well-controlled bank of pilot-scale flotation cells has shown that the above assumptions are well justified.

For the copper, the test work failed to yield a set of valid empirical relationships that would explain the observed variation in kinetic and probability function parameters brought about by changes in the levels of the operating variables. This may partly be due to basing the determination of these parameter values on the copper analysis of the entire flotation concentrate

TABLE 7

Verification Tests for Equations 3 to 6

Test No.	Responses	Eq. No.	Predicted Value (%)	Measured Value (%)	95% Confidence Interval on Predicted (%)
18*	Cu-Conc	3	2.56	2.38	1.68 - 3.44
18	Cu-Recov	4	89.3	91.2	87.7 - 90.9
18	Ni-Conc	5	4.71	4.60	3.74 - 5.68
18	Ni-Recov	6	69.3	71.9	63.1 - 75.5
19**	Cu-Conc	3	3.64	3.35	2.76 - 4.52
19	Cu-Recov	4	86.9	88.5	85.3 - 88.5
19	Ni-Conc	5	5.15	5.70	4.18 - 6.12
19	Ni-Recov	6	50.5	58.6	44.3 - 56.7

\* Test 18: Variables were pH - 9.5, Z-200 - 0.102 lb/ton, R-238 - 0.03 lb/ton

\*\* Test 19: Variables were pH - 7.5, Z-200 - 0.034 lb/ton, R-238 - 0.05 lb/ton.

rather than on individual size fractions. The parameter values shown for copper may represent the summation of individual values for several types of particles. Each of these particle types (e.g. pure mineral, middling, gangue) could have a different value and some of these may be independent of changes in the operating variable levels.

Copper recoveries in the tests shown on Table 4 ranged from 84.5 to 90.9%, while nickel recoveries ranged from 33 to 71.9%. The reagent levels which gave the lowest recovery of the nickel (33%) also recovered 84.5% of the copper. Further increases in the levels of these reagents resulted in an additional 38.9% recovery for nickel, but only 6.4% for copper. Thus the test work shows that the nickel flotation is much more sensitive to changes in the variable levels than is the copper flotation.

For the nickel, the test work yielded a set of valid relationships that explained the observed variation in the kinetic and probability function parameters. Based on these relationships, the recovery and nickel concentration of the concentrate should be improved by applying the following conditions in the flotation circuit:

- 1) a pH of about 10,
- 2) using 0.102 lb of Z-200 per ton ore,
- 3) using 0.06 lb of R-238 per ton ore.

The above conditions would recover 70 to 75% of the nickel and at least 90% of the copper.

Separate copper and nickel concentrates could be made by re-floating the bulk concentrate at a pH of 11.3 or higher. This procedure would result in a copper-rich concentrate and a nickel-rich tailing. It is doubtful, however, that this step would be advantageous, since it would not likely result in a satisfactory separation of the two metals.

#### ACKNOWLEDGEMENTS

The contribution of other members of the Extraction Metallurgy Division staff to this work is gratefully acknowledged. Mr. D. Fraser of the Hydrometallurgy Section assisted with the regression analysis calculations. The chemical analysis was done in the Chemical Analysis Section under the direction of Mr. J.C. Ingles and principally by Mr. R.J. Guest. Acknowledgement is also made of the work of Mr. J.L. Fleury who, as laboratory technician, assisted with the experimental work.

The kind co-operation of Mr. C.P. Moore, mine manager of the Werner Lake property, and of Mr. B. Weir, the mine geologist, in supplying the necessary samples for this work is gratefully acknowledged.

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