FINAL REPORT

to

Minnesota Environmental Quality Board

Copper-Nickel Study

Mineral Processing Studies - Flotation Tests

UNIVERSITY OF MINNESOTA
INSTITUTE OF TECHNOLOGY
MINNEAPOLIS, MINNESOTA 55455

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Minnesota Environmental Quality Board
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Mineral Processing Studies - Flotation Tests

by

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April 24, 1978

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9004 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	6.37		0.335		5.04		7.96	
B	0.0412		0.0874		0.0621		0.158	
Be	0.00012		nd		0.00009		0.00014	
Ca	3.45		0.151		2.75		4.4	
Cu	1.16	1.35	8.2	9.66	0.135	0.19	0.0336	0.080
Fe	23.4	17.69	47.6	47.33	31.5	29.84	12.4	9.79
Mg	2.69		0.162		1.96		3.28	
Mn	0.11		0.0068		0.0791		0.138	
P	nd		nd		nd		0.026	
Ba	0.0278		0.0028		0.027		0.115	
Se	nd		0.04		nd		nd	
Te	0.422		0.822		0.556		0.272	
	nd		0.003		nd		nd	
Si	0.177		0.0112		0.332		1.32	
Sr	0.0149		0.00078		0.0121		0.0195	
Zr	0.0059		0.0012		0.0062		0.0095	
Ti	0.645		0.0251		0.468		0.846	
V	0.0212		0.00081		0.0151		0.0267	
Zn	0.0177		0.0003		0.0141		0.0207	
Th	nd		nd		nd		nd	
K	0.714		0.013		0.552		0.948	
Na	1.16		0.12		0.927		1.56	
Cd	nd		nd		nd		nd	
Cr	0.0239		nd		0.0362		0.0312	
Co	0.0363	0.048	0.22	0.27	0.009	0.017	0.0038	0.010
Ag	nd		0.0017		nd		nd	
Mo	nd		0.0089		nd		nd	
Ni	0.422	0.54	2.96	3.40	0.1	0.135	0.0175	0.041
Pb	nd		nd		nd		nd	
Sb			<0.0001					
Bi			0.0096					

*Conventional AA analyses

TABLE 14. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9002 (TEST 21 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Regr Cl 4 Conc (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	9.43		0.759		9.33		9.50	
B	0.0157		nd		0.0766		0.129	
Be	nd		nd		nd		nd	
Ca	5.69		0.47		5.63		5.69	
Cu	0.592	0.67	22.30	22.62	0.0362	0.41	0.40	0.074
Fe	10.30	10.90	34.30	33.26	10.00	11.15	10.20	10.87
Mg	6.09		1.10		6.02		5.95	
Mn	0.12		0.0175		0.128		0.111	
P	0.248		5.69		0.145		0.222	
Ba	0.0283		0.0022		0.0597		0.0868	
Se	nd		nd		nd		nd	
)	nd		nd		nd		nd	
As	nd		nd		nd		nd	
Si	0.244		0.0287		0.773		1.23	
Sr	0.0272		0.0021		0.0276		0.0272	
Zr	0.0046		0.0010		0.0081		0.0064	
Ti	1.24		0.0524		1.41		0.80	
V	0.0214		0.0130		0.0223		0.0196	
Zn	0.0164		0.228		0.0105		0.0156	
Th	0.0014		0.0010		0.0014		0.0014	
K	0.30		0.13		0.32		0.38	
Na	2.17		0.20		2.30		2.18	
Cd	nd		0.0020		nd		nd	
Cr	0.0171		0.00292		0.0138		0.0427	
Co	0.0137	0.020	0.136	0.13	0.0097	0.016	0.0132	0.013
Ag	0.00055		0.00568		0.00041		0.00068	
Mo	nd		nd		nd		nd	
Ni	0.134	0.151	3.29	3.30	0.0334	0.171	0.143	0.045
)	nd		0.0090		nd		nd	
Sb			<0.0001					
Bi			0.0104					

*Conventional AA analyses

TABLE 9. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON US9001 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.51		0.653		8.9		8.92	
B	0.15		0.0544		0.123		0.134	
Be	0.00009		0.00001		0.00009		0.00009	
Ca	5.62		0.416		5.71		5.83	
Cu	0.315	0.39	16.1	15.01	0.212	0.21	0.032	0.075
Fe	8.88	12.44	46.2	46.06	9.1	12.75	8.08	11.99
Mg	3.66		0.486		3.62		3.74	
Mn	0.11		0.0212		0.107		0.112	
P	0.133		2.24		0.16		0.072	
Ba	0.103		0.0343		0.0919		0.0956	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
	nd		0.005		nd		nd	
Si	1.41		0.59		1.18		1.3	
Sr	0.0228		0.00199		0.0232		0.0237	
Zr	0.0111		0.0022		0.0128		0.0085	
Ti	1.0		0.0718		0.959		0.967	
V	0.0174		0.00637		0.0188		0.0165	
Zn	0.0128		0.148		0.0147		0.0097	
Th	nd		nd		0.0007		nd	
K	0.164		0.042		0.126		0.123	
Na	2.05		0.206		2.04		2.14	
Cd	nd		nd		nd		nd	
Cr	0.0178		0.11		0.0671		0.0135	
Co	0.0097	0.018	0.145	0.162	0.0099	0.019	0.0062	0.018
Ag	nd		0.004		nd		nd	
Mo	nd		0.0067		0.0014		nd	
Ni	0.0813	0.10	2.78	2.56	0.101	0.115	0.026	0.035
Pb	nd		nd		nd		nd	
			<0.0001					
Bi			0.0088					
Hg**								

*Conventional AA analyses
**0.0000001% = 1 ppb

TABLE 9. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON DP9002 (TEST 8 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	7.25		0.223		6.18		7.93	
B	0.0117		nd		0.0118		0.0203	
Be	0.00009		nd		0.00008		0.00009	
Ca	5.35		0.144		4.19		5.9	
Cu	0.835	0.89	20.5	19.98	0.296	0.31	0.0419	0.053
Fe	13.0	15.25	43.2	38.81	17.9	23.56	10.3	12.11
Mg	3.44		0.128		2.83		3.83	
Mn	0.128		0.00807		0.103		0.143	
P	0.122		0.389		0.111		0.098	
Ba	0.0255		0.0021		0.0225		0.0326	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
As	nd		0.0020		nd		nd	
Si	0.113		0.0148		0.0762		0.21	
Sr	0.0205		0.0006		0.0177		0.0223	
Zr	0.0121		0.00102		0.0109		0.0128	
Ti	1.57		0.0419		1.07		1.57	
V	0.0186		0.00155		0.0178		0.0213	
Zn	0.0220		0.217		0.017		0.0149	
Th	nd		nd		0.00016		nd	
K	0.354		0.009		0.343		0.387	
Na	1.75		0.04		1.49		1.93	
Cd	nd		nd		nd		nd	
Cr	0.0184		nd		0.0495		0.0151	
Co	0.0204	0.025	0.232	0.26	0.0138	0.015	0.0063	0.015
Ag	0.00028		0.0041		0.00036		0.00009	
Mo	nd		nd		nd		nd	
Ni	0.1810	0.215	3.25	3.21	0.122	0.16	0.0182	0.034
Pb	nd		nd		nd		nd	
Sb			<0.0001					
Bi			0.0096					

*Conventional AA analyses

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON IP9003 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	9.06		0.804		9.22		9.46	
B	0.245		0.0619		0.265		0.263	
Be	0.00003		nd		0.00004		0.00003	
Ca	5.46		0.537		5.53		5.68	
Cu	0.588	0.66	18.2	19.96	0.755	0.83	0.0665	0.055
Fe	9.14	11.45	33.9	34.92	9.21	11.50	8.31	10.25
Mg	5.65		1.38		4.68		5.69	
Mn	0.105		0.0161		0.0882		0.111	
P	nd		nd		nd		nd	
Ba	0.162		0.0147		0.165		0.175	
Se	nd		nd		nd		nd	
[illegible]	0.233		0.567		0.233		0.233	
As	nd		nd		nd		nd	
Si	2.59		0.259		2.58		2.81	
Sr	0.0299		0.0024		0.0299		0.0312	
Zr	0.0084		0.0017		0.0093		0.0086	
Ti	0.639		0.0362		0.495		0.613	
V	0.0104		0.00089		0.00828		0.0107	
Zn	0.0082		0.0017		0.0113		0.0081	
Th	nd		nd		nd		nd	
K	0.326		nd		0.417		0.347	
Na	2.22		0.216		2.1		2.32	
Cd	nd		nd		nd		nd	
Cr	0.0405		0.00932		0.0798		0.0353	
Co	0.0113	0.028	0.102	0.16	0.0131	0.025	0.0074	0.019
Ag	nd		0.0042		0.0008		nd	
Mo	nd		nd		0.0032		0.0004	
Ni	0.17	0.21	3.08	3.56	0.26	0.31	0.0589	0.078
[illegible]	nd		0.003		nd		nd	
Sb			<0.0001					
Bi			0.0112					

*Conventional AA analyses

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PROUDCTS ON IP9002 -- (TEST 41 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Regr Cl 4 Conc (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	11.00		1.13		10.60		11.10	
B	0.00044		0.00005		0.114		0.111	
Be	nd		nd		nd		nd	
Ca	6.64		0.769		6.40		6.64	
Cu	0.422	0.45	16.70	16.60	0.203	0.199	0.0297	0.045
Fe	8.02	9.43	30.20	29.52	9.34	10.00	8.21	8.32
Mg	4.74		2.50		4.95		4.80	
Mn	0.107		0.0315		0.106		0.105	
P	0.176		2.67		0.167		0.128	
Ba	0.0136		0.0026		0.0759		0.0742	
Se	nd		nd		nd		nd	
e	nd		nd		nd		nd	
As	0.011		0.002		0.012		0.010	
Si	0.0469		0.0412		1.09		1.06	
Sr	0.035		0.00317		0.0321		0.0343	
Zr	0.0021		0.0011		0.0045		0.0040	
Ti	0.4570		0.0361		0.514		0.583	
V	0.0129		0.0119		0.0153		0.0134	
Zn	0.0129		0.179		0.0156		0.0111	
Th	0.0011		0.0009		0.0012		0.0012	
K	0.16		0.18		0.20		0.15	
Na	2.42		0.244		2.35		2.54	
Cd	nd		0.003		nd		nd	
Cr	0.02		0.0108		0.0469		0.019	
Co	0.0102	0.017	0.147	0.166	0.01	0.020	0.0075	0.013
Ag	0.00052		0.00446		0.00056		0.00035	
Mo	nd		0.0008		0.0002		nd	
Ni	0.099	0.15	3.21	3.20	0.0847	0.096	0.0302	0.044
)	nd		0.013		nd		nd	
Sb			<0.0001					
Bi			0.0112					

*Conventional AA analyses

and graphite, as well as in the separation of hydrous minerals, without further regrinding.

4.5 PRECIOUS METALS

Duluth gabbro contains traces of gold, silver, and the platinum group metals amounting, according to some estimates, to as high as 10 percent of the gross value of the copper and nickel. Only a limited amount of the analytical data is available in the literature on the precious metals in bulk sulfide concentrates on Inco pit samples and none on any crude samples. Table 6 summarizes the results of precious metals analyses on flotation concentrates of the Inco pit sample reported by different laboratories. It is interesting to note that all the results are in good agreement although they were for different bulk flotation concentrates.

The precious metals analyses of several selected concentrates are given in Table 7. The results scattered appreciably and there appeared to be no particular correlation between the precious metal contents and either the copper or nickel contents. The concentrate of one of the semi-massive samples (AX9007) analyzed high in precious metals, but the others (AX9004 and AX9006) analyzed low. It becomes of interest to investigate the manner in which precious metals are associated with sulfide minerals. Nevertheless the values in Table 7 averaged 0.04 ounce of gold, 1.3 ounce of silver, 0.02 ounce of platinum and 0.07 ounce of palladium per ton.

TABLE 6. PRECIOUS METALS ANALYSES OF FLOTATION CONCENTRATES FROM INCO PIT SAMPLES

Source	Analytical Method	Percent		Ounces per ton			
		Cu	Ni	Au	Ag	Pt	Pd
USBM[8]	Spectrographic	10.0	2.2	0.04	1.1	0.036	0.120
		14.4	3.1	0.04	1.5	0.030	0.128
		12.2	2.5	0.04	1.4	0.021	0.122
Inco[12]		13.3	3.6	0.025	0.86	0.035	0.10
MRRC[7]	Spectrographic	27.9	0.33	0.10	1.3	0.03	0.13
		1.0	11.7	0.05	1.2	0.03	0.10
This Report*	ICP	16.7	2.6	-	1.01 0.81	-	-
		16.6	3.2	-		-	-
Thingvold**	NAA	16.7	2.6	0.020	0.71	-	-

* Section 3.1
**Letter dated July 13, 1977

TABLE 7. PRECIOUS METALS ANALYSES OF FLOTATION CONCENTRATES FROM VARIOUS DULUTH GABBRO SAMPLES

Sample	Test No.	Percent		Ounces per ton			
		Cu	Ni	Au	Ag	Pt	Pd
IP9003	6 & 7*	18.91	3.85	0.050	1.18	0.037	0.092
AX9004	14**	8.28	3.20	0.010	0.36	0.003	0.021
AX9005	7	19.99	3.36	0.031	2.10	0.020	0.110
	Pilot Plant***	15.02	2.59	0.028	1.34	0.018	0.055
AX9006	2	23.02	1.86	0.003	1.36	0.007	0.007
AX9007	2	23.98	1.35	0.140	1.44	0.008	0.120

* C1 4 Conc from two tests mixed
**Duplicate test sample
***February 23, 1978, 5-7 p.m.

UNIVERSITY OF MINNESOTA
TWIN CITIES

Mineral Resources Research Center
56 East River Road
Minneapolis, Minnesota 55455

8 August 1978

Dr. Peter Kreisman
Research Manager
Copper-Nickel Study
138 Hennepin Square Building
2021 East Hennepin Avenue
Minneapolis, Minnesota 55413

Dear Pete:

Enclosed please find five copies of the final report titled, "Mineral Processing Studies - Hydrometallurgical Processing of Concentrates."

Also enclosed are five copies each of the following addenda to a report titled, "Mineral Processing Studies - Flotation Tests."

1. Page 80 (Sb and Bi analyses added)
2. Page 113 (Sb and Bi analyses added)
3. Page 137 (Sb and Bi analyses added)
4. Page 171 (Sb and Bi analyses added)
5. Page 228 (Sb and Bi analyses added)
6. Page 280 (Sb and Bi analyses added)
7. Page 358 (Second paragraph under PRECIOUS METALS)
8. Page 359 (Precious metals analyses in Table 7)

Sincerely yours,

I. Iwasaki
Professor

II:dh

Enclosures(13)

TABLE OF CONTENTS

1.0 INTRODUCTION

The primary objectives of the present investigation were to assess not only the concentrating characteristics of the Duluth gabbro copper-nickel ore, but also the potential impact on the environment of the processing by the possible generation of dust particles, the release of copper and nickel as well as trace element ions, and the presence of any residual flotation reagents in process water that might be discharged, either intentionally or accidentally. The coarser the mesh-of-grind, the smaller will be the possibility of dust being generated, since the amount of the fines will be less. The recoveries of copper and nickel, however, may suffer due to insufficient liberation with a coarser grind and the residual sulfides in the tailings could increase, which in turn would increase the potential release of copper, nickel, and trace element ions upon oxidation in tailing ponds. Conversely, with a finer mesh-of-grind, the residual sulfides in the tailings should decrease, but the amount of dust generated would be expected to increase. Determination of size distribution characteristics and size fractionation followed by a mineralogical study coupled with chemical analyses on each size fraction of the flotation products could, therefore, shed some light on the mineralogy of potential dust particles and on the nature of the association of residual sulfides in the tailings.

Eleven different samples from the study region representing variations in lateral location and mineralizations, as well as in depth at one location, were received from the MEQB Copper-Nickel Study group. The locations where the eleven samples were obtained are shown in Figure 1. A brief description

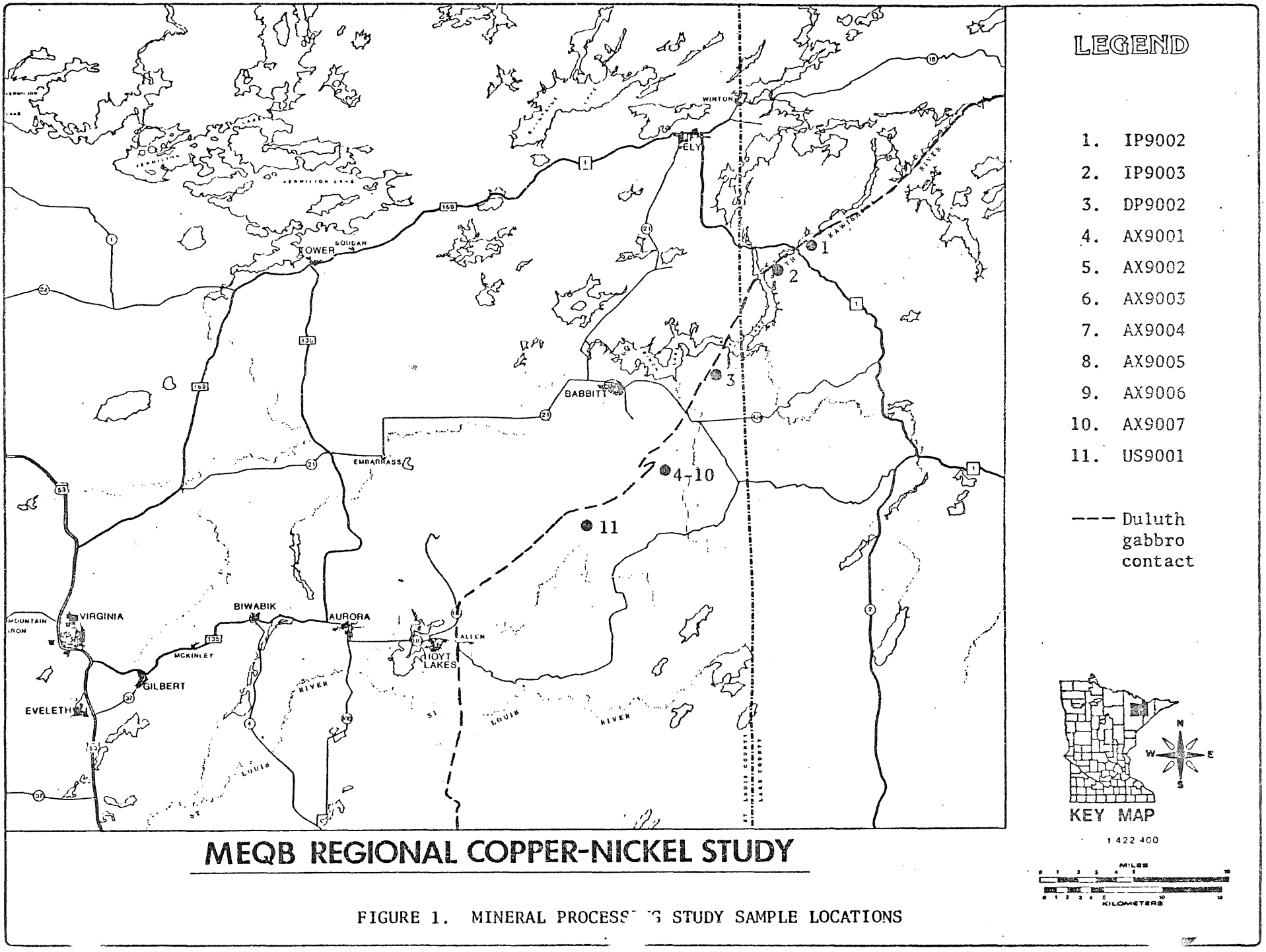


FIGURE 1. MINERAL PROCESS[illegible]G STUDY SAMPLE LOCATIONS

of each sample and its head analysis are given in Tables 1 and 2. Their mineralogical compositions are presented in Table 3. Table 3 was received from Professor P.W. Weiblen and Mr. R.J. Stevenson of the Department of Geology and Geophysics, University of Minnesota.

These samples were individually examined by performing bulk sulfide flotation tests of their concentration characteristics. In these tests the possibilities of concentrating unusual trace elements and of liberating hydrous minerals selectively by grinding that would result in the formation of fibers were investigated. The concentrations of residual flotation reagents and heavy-metal ions in the pulp solutions were determined, and mineralogical studies on the flotation concentrates and tailings for liberation characteristics were made. Each flotation tailing pulp was left exposed to the air, as in a tailing pond, and the pulp solution was analyzed periodically to investigate if residual flotation reagents decomposed and if any trace element ions were released upon aging. The tailing samples were also used for environmental leaching studies and germination studies.

The flotation tests were performed by Mr. A.S. Malicsi, the size distribution and the size fractionation tests by Mr. R.J. Lipp, both of the Mineral Resources Research Center, and the mineralogical studies by Mr. J.S. Walker of the Department of Geology and Geophysics, University of Minnesota.

TABLE 1. DESCRIPTION OF DULUTH GABBRO TEST SAMPLES

IP9002:	Inco's Spruce Road test pit sample
IP9003:	Inco's Maturi shaft sample from depths of 798 feet to 905 feet
DP9002:	Mineralized gabbro sample from a stockpile near Dunka Pit
US9001:	Mineralized gabbro sample from a pile in the U.S. Steel Research Center
AX9001:	Minnamax leach pad sample
AX9002:	AMAX shaft composite sample from depths of 1249 feet and 1312 feet
AX9003:	AMAX shaft composite sample from depth of 1338 feet and 1343 feet
AX9004:	AMAX semi-massive, mineralized rock sample
AX9005:	AMAX mineralized rock sample from MRRC Sample No. 2
AX9006:	AMAX semi-massive, mineralized rock sample
AX9007:	AMAX semi-massive, mineralized rock sample

TABLE 2. HEAD ANALYSES OF TEST SAMPLES

	Copper	Nickel	Cobalt	Iron	Sulfur	Titanium Dioxide	Graphite Carbon
IP9002	0.45	0.15	0.017	9.43	0.98	(1.0)	0.047
IP9003	0.69	0.205	0.015	11.49	1.23	0.73	0.091
DP9002	0.81	0.25	0.037	15.03	3.93	2.39	0.066
US9001	0.40	0.127	0.018	10.05	1.21	1.69	0.028
AX9001	0.31	0.085	0.018	9.50	0.66	2.31	0.114
AX9002	0.60	0.14	0.014	9.06	1.00	1.25	0.10
AX9003	0.64	0.15	0.021	11.04	1.21	1.54	0.18
AX9004	1.30	0.56	0.038	19.48	8.42	1.17	0.22
AX9005	0.72	0.175	0.028	12.88	1.52	2.06	0.10
AX9006	6.38	0.505	0.050	11.86	8.32	-	0.44
AX9007	3.20	0.228	0.027	7.42	3.42	-	0.36

TABLE 3. MINERALOGICAL COMPOSITION OF TEST SAMPLES
(By P.W. Weiblen and R.J. Stevenson)

	IP9002	IP9003	DP9002	US9001	AX9001	AX9002	AX9003	AX9004	AX9005
Plagioclase	65.443	66.166	47.242	64.881	59.112	61.457	47.363	47.855	47.403
Sericite	2.683	0.373	0.069	0.188	2.176	2.518	1.911	0.091	0.245
Olivine	15.308	17.123	10.766	16.173	10.510	13.586	18.267	1.513	25.841
Clinopyroxene	3.723	3.717	26.102	7.237	11.185	6.809	5.024	2.656	7.622
Orthopyroxene	0.231	0.618	2.315	1.834	3.716	2.882	1.407	18.472	2.132
Monocrystalline amphibole	1.387	1.055	-	-	3.567	0.095	12.225	0.025	0.066
Fibrous amphibole	0.934	0.077	-	-	0.288	0.335	0.850	0.024	-
Chlorite	2.078	2.612	0.403	1.349	1.136	1.950	3.887	0.145	1.337
Serpentine	0.731	0.026	0.014	0.097	0.257	0.441	0.033	-	7.659
Iddingsite	0.079	0.064	0.053	0.172	0.075	0.006	0.019	-	0.194
Talc	0.061	0.463	-	-	-	-	-	-	0.006
Biotite	1.696	1.788	5.031	3.785	1.738	3.037	3.010	4.475	2.431
Smectite	0.025	0.026	-	0.051	0.021	0.030	0.053	-	-
Celadonite	-	-	-	-	-	-	-	-	-
Opaques	3.474	5.365	7.923	4.025	5.098	4.776	5.190	19.239	4.720
Chalcopyrite-cubanite	1.403	1.778	1.341	0.875	0.769	0.962	1.458	3.231	1.355
Pentlandite	0.117	0.025	0.341	0.102	0.037	0.012	0.113	0.161	0.043
Pyrrhotite	0.953	1.571	3.073	0.882	0.844	1.093	1.105	12.816	0.497
Ilmenite	-	0.051	0.003	-	0.205	0.176	0.078	0.777	0.134
Magnetite	0.998	1.938	3.140	2.164	3.242	2.518	2.432	1.787	2.692
Graphite	-	-	0.025	-	-	0.015	0.004	0.467	-
Spinel	-	-	-	-	-	0.009	-	-	-
Myrmekite	0.288	0.065	-	0.106	-	0.042	-	-	-
Apatite	0.050	0.013	0.074	0.075	0.085	0.149	0.172	0.118	0.346
Epidote	0.698	0.322	-	0.017	0.953	0.203	0.470	-	-
Allanite	0.007	0.051	-	-	-	0.090	-	-	-
Calcite	0.089	0.077	0.006	0.007	0.056	0.065	0.017	-	-
Quartz	-	-	-	-	-	-	-	0.037	-
Cordierite	0.013	-	-	-	0.027	1.515	0.106	5.350	-

2.0 DEVELOPMENT OF TEST PROCEDURES

In order to provide the analytical samples for identifying and counting fibrous mineral particles and the flotation products for studying mineralogy and environmental leaching, the bench-scale flotation procedures as well as the sampling techniques must be established. In this section the procedure for preparing samples, the methods of sampling for solids and water, the procedures for analyzing the collector and the frother used in the flotation, the methods for size fractionation and for the determination of size distributions, and the developmental work leading to standardized flotation procedures are presented. Since the Inco pit sample (IP9002) was available in a large enough quantity at the Mineral Resources Research Center initially, the developmental work on the test procedures was made mainly with this sample. Distilled water was used throughout, both in the preparation of reagents and in the test work.

2.1 SAMPLE PREPARATION

For each of seven samples, excluding IP9002 and IP9003, 200 to 500 pounds of crude sample received in coarse lumps was first crushed to minus 1/4 inch through a laboratory jaw crusher, then to minus 1/8 inch through a coffee mill. The crushed sample was screened at 10 mesh, and the oversize crushed through rolls, the minus 10-mesh fraction being screened out after each stage until all the material passed through this size. The minus 10-mesh material was then well mixed and split into 1200-gram lots for flotation testing. The flowsheet for the crushing operations is shown in Figure 1.

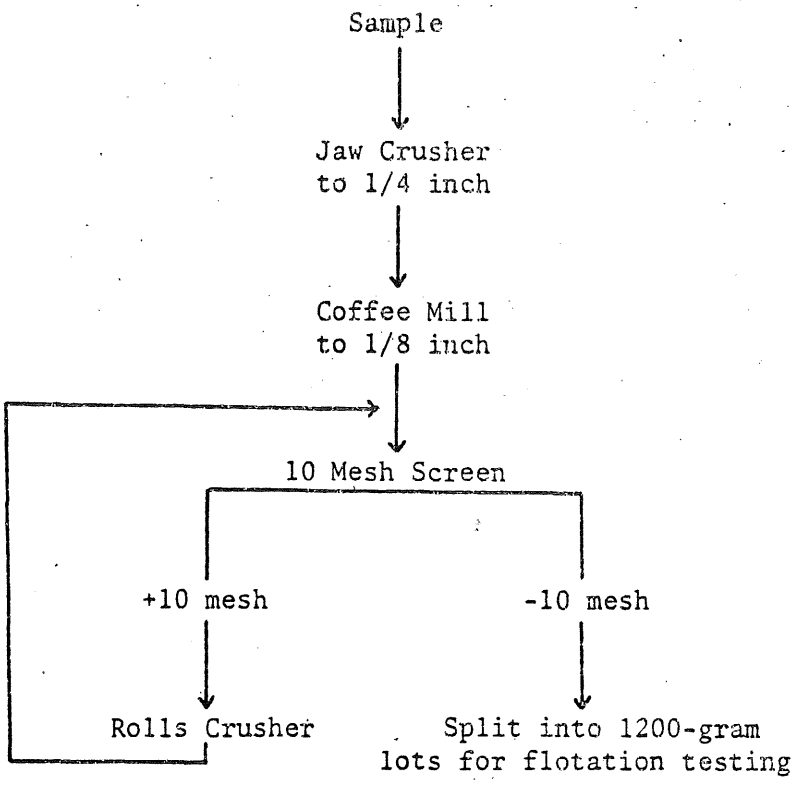


FIGURE 1. FLOWSHEET FOR CRUSHING OF SAMPLES

The grinding characteristics of each crude sample were ascertained by determining the size distribution of a sample ground in a laboratory mill for different periods of time. Essentially all the testwork was carried out on samples ground in a stainless steel rod mill, but to test the effect of grinding media a few tests were made on samples ground in a carbon steel ball mill.

Twelve-hundred-gram lots of a crude sample crushed through 10 mesh were ground in a stainless steel rod mill at 50 percent solids for 15, 20, 30, and 60 minutes and their size distributions were determined by wet screening. The results of the size distribution determinations are given in Table 1 and plotted in Figure 2. Similar determinations were made by grinding in a carbon steel ball mill and the results are also

TABLE 1. SIZE DISTRIBUTION OF IP9002 SAMPLE GROUND IN LABORATORY GRINDING MILLS AS A FUNCTION OF GRINDING TIME
(SAMPLE WEIGHT: 1200 GRAMS AT 50 PERCENT SOLIDS)

Size, mesh	Feed (-10 mesh)	Stainless Steel Rod Mill				Carbon Steel Ball Mill	
		15 min	20 min	30 min	60 min	30 min	60 min
10	0.2	-	-	-	-	-	-
14	23.6	-	-	-	-	-	-
20	13.2	-	-	-	-	-	-
28	14.2	-	-	-	-	-	-
35	10.2	0.8	-	-	-	-	-
48	9.2	8.1	2.0	-	-	-	-
65	5.9	17.4	10.0	-	-	-	-
100	6.6	19.8	20.0	5.4	-	3.4	0.4
150	6.6	16.6	19.5	16.6	4.0	13.4	1.3
200	3.4	12.6	13.5	21.0	11.5	22.2	9.6
270	1.8	4.4	9.0	15.2	22.8	15.6	16.2
325	1.0	3.0	5.0	6.8	10.5	8.4	12.0
400	0.6	2.4	2.4	5.0	7.4	3.4	6.3
500	1.3	2.8	4.1	5.4	8.5	7.1	12.4
-500	2.2	12.1	14.5	24.6	35.3	26.5	41.8

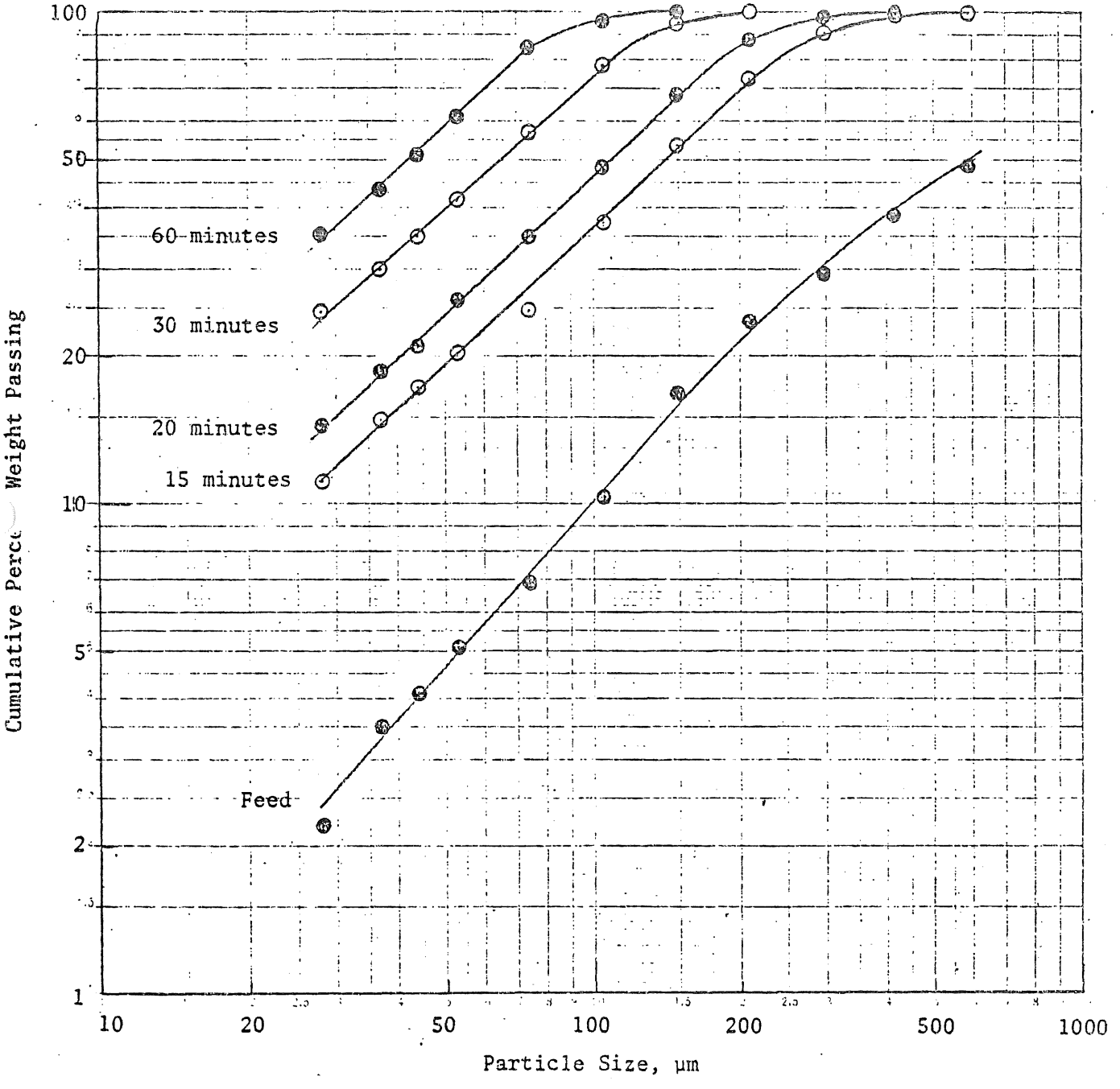


FIGURE 2. SIZE DISTRIBUTIONS OF IP9002 SAMPLE AS A FUNCTION OF GRINDING TIME

included in the table. The size distributions of the ground samples follow straight lines which may be represented by the Schuhmann equation

$$y = 100 \cdot \left(\frac{x}{k}\right)^m \quad \ldots . \quad (1)$$

where

y: cumulative weight percent finer than size x

x: particle size, μm

k: size modulus, μm

m: distribution modulus

These lines are seen to be parallel to each other, with a slope, or distribution modulus of 0.92. The samples ground in a carbon steel ball mill gave virtually identical slopes to those ground in a stainless steel rod mill. It was concluded, therefore, that the size distribution characteristics of the ground products with these two grinding mills were thought to be essentially the same. The size moduli, obtained by extrapolating these lines to 100 percent, or a hypothetical coarsest size in a sample, may be considered, therefore, to represent the size distributions of the ground products. In Figure 3 the size moduli thus obtained are plotted against the corresponding times of grind. These straight-line relationships enable one to estimate the time-of-grind needed to obtain the desired mesh-of-grind. In practice, the size of a sample may often be represented by the 80 percent passing size. Since the size distribution lines are parallel to each other in Figure 2, it is expected that the line for the 80 percent passing size in Figure 3 will parallel those for the size moduli. The nominal mesh-of-grind, the grinding time, the size modulus and the 80 percent passing size for the present sample are summarized in Table 2.

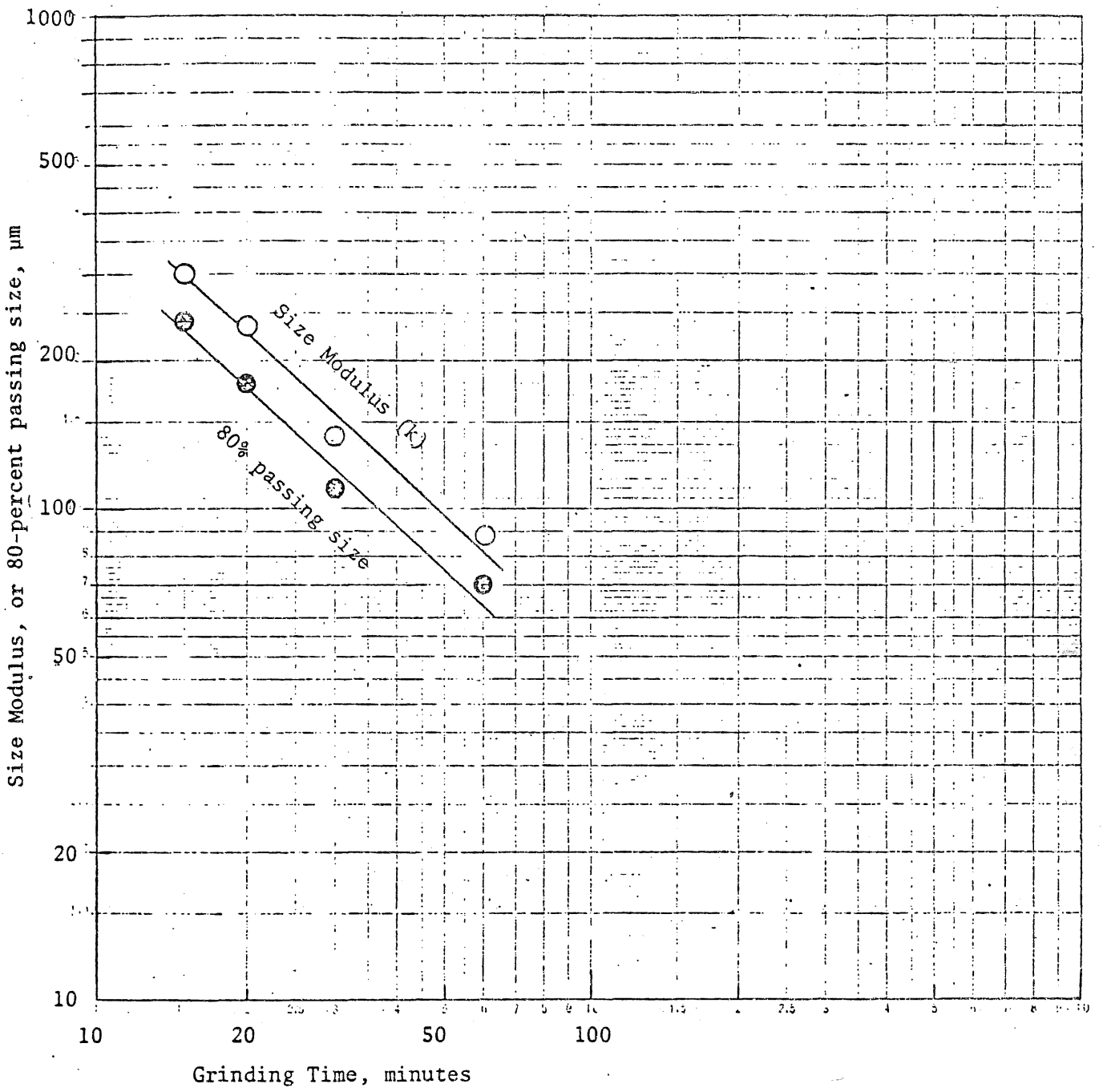


FIGURE 3. SIZE MODULI AND 80-PERCENT PASSING SIZE OF IP9002 SAMPLE AS A FUNCTION OF GRINDING TIME

TABLE 2. BATCH GRINDING CHARACTERISTICS OF IP9002 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50% SOLIDS)

Nominal Mesh-of-grind	Grind Time Minutes	Size Modulus k, μm	80% passing μm
Feed	0	-	1220
-48 mesh	15	300	240
-65 mesh	20	235	180
-100 mesh	30	140	110
-200 mesh	60	88	70

2.2 PULP SAMPLING PROCEDURES

In the present project a number of representative pulp samples of feeds, concentrates and tailings must be obtained for size fractionation and for the determination of size distribution and fibrous mineral contents without filtration or drying. In order to ascertain if the splitting of a portion of a rougher tailing pulp agitated in a Denver cell with the air valve closed might produce a sample representative of the whole pulp, ten samples of flotation feed ground to minus 200 mesh, approximately 25 milliliters each, were siphoned from a point about half way down the pulp level in the Denver cell. The samples were labeled in the order taken, dried, weighed and assayed for copper and nickel. Table 3 shows the weights and the analytical results of the ten samples as well as of the remaining pulp. It is apparent in the table that there are no systematic variations in the copper and nickel content and that the standard deviations are quite small.

TABLE 3. ANALYTICAL RESULTS OF FEED SAMPLES TAKEN AT HALF WAY DOWN THE PULP LEVEL IN A DENVER CELL (200 MESH GRIND)

Sample	Weight, grams	% Cu	% Ni
1	13.5	0.43	0.135
2	13.8	0.43	0.148
3	14.7	0.44	0.140
4	14.3	0.44	0.135
5	14.8	0.44	0.153
6	14.0	0.43	0.150
7	14.8	0.43	0.139
8	14.0	0.44	0.140
9	13.8	0.43	0.142
10	14.6	0.43	0.167
Remaining Pulp	1057.0	0.44	0.145
Composite	1199.3	0.439	0.147
Sample Average	14.23	0.434	0.145
Std. Deviation	0.47	0.005	0.010

An additional test was carried out to check the size distribution of samples taken in this manner. Three samples, approximately 100 milliliters each, were siphoned out of a rougher flotation tailing at levels one-fourth, one-half and three-fourths the way down the pulp level in the Denver cell. The size distributions of the three samples were determined by wet screening and the results are compared in Table 4 with that of a rougher flotation tailing obtained under identical test conditions. In Figure 4 cumulative percent weights are plotted against particle size. This Schuhmann plot tends to smooth out the fluctuation in weight percents of individual size fractions due to faulty screens and to inefficient screening procedure. It is readily apparent in the figure that the size distributions of the four samples are in good agreement. It was concluded, therefore, that pulp samples removed by siphoning from an agitated pulp in a Denver cell could produce representative tailing samples.

The pulps of concentrates could not be dispersed in water for sampling in a similar manner because of hydrophobic coating with the collector. It was found that the addition of denatured alcohol equal to the volume of the water destroyed the flotation tendency of the concentrate and the particles appeared to be fully dispersed in the alcohol-water mixture. The pulps of concentrates, therefore, were sampled after adding an equal volume of denatured alcohol to the flotation froth products.

For the determination of size distributions, the trace element analyses of the sized products, and for the fiber count analyses, the most convenient amount of pulp sample was about 10 grams (dry basis). Hence, for feed and tailing pulps six samples each of 15 and 20 milliliters, respectively, and for concentrate pulps four 400-millilter samples were obtained by siphoning

TABLE 4. SCREEN ANALYSES OF A ROUGHER TAILING SAMPLE TAKEN AT THREE DIFFERENT DEPTHS IN A DENVER CELL (100 MESH GRIND)

Size, Mesh	Total Sample*	Level 1**	Level 2**	Level 3**
65	1.22	1.59	1.00	1.72
100	14.36	12.80	10.40	13.10
150	25.78	35.49	37.20	36.63
200	21.91	14.88	7.50	13.10
270	11.54	12.93	8.60	9.88
325	3.91	1.34	1.90	3.44
400	5.05	4.88	1.30	4.08
500	5.48	3.54	4.00	4.08
-500	10.75	12.55	12.00	13.97

* Screen analysis made on a total sample
**Approximately 100 milliliters of pulp siphoned out for screen analyses

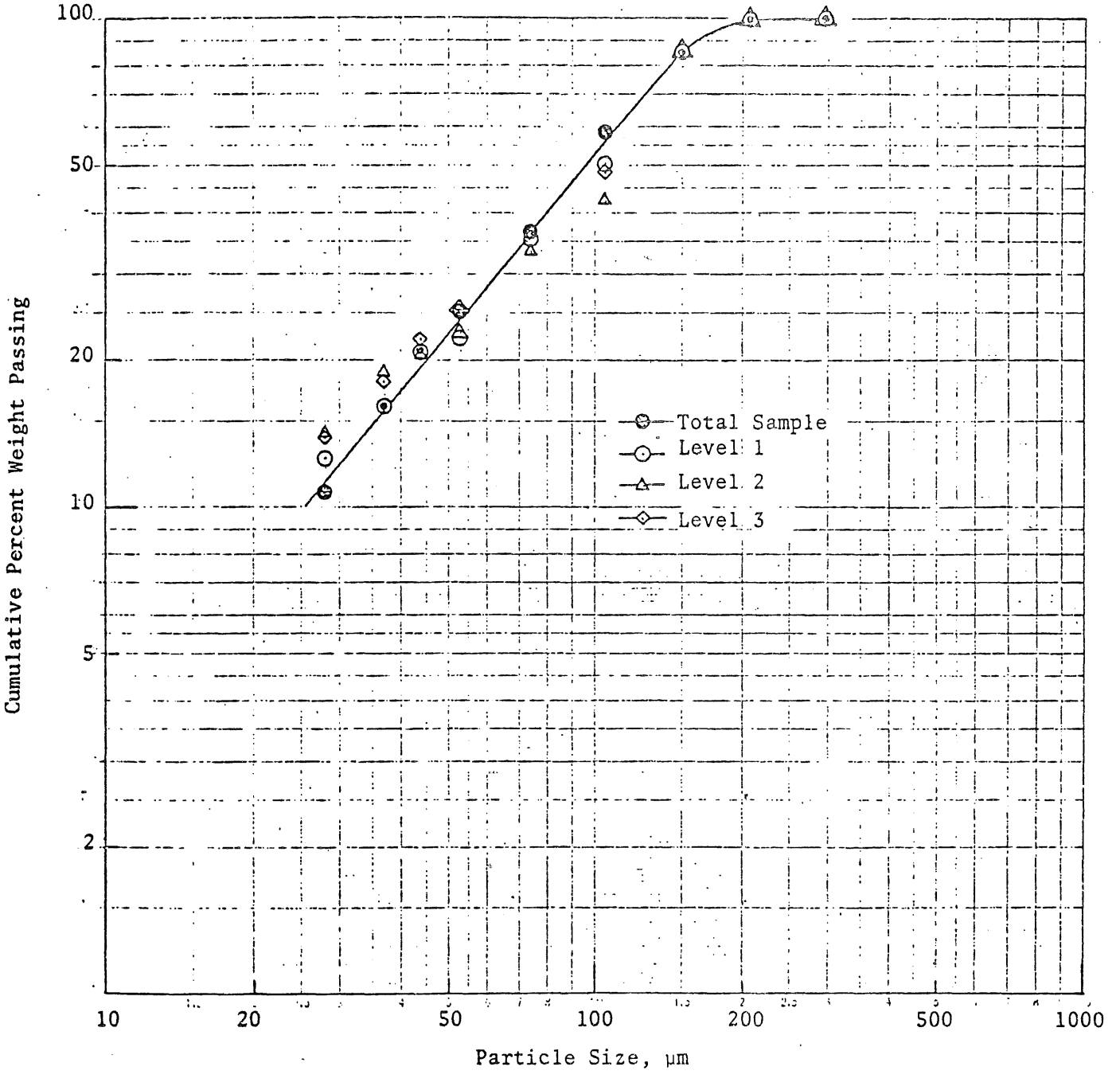


FIGURE 4. SIZE DISTRIBUTIONS OF A ROUGHER TAILING SAMPLE TAKEN AT THREE DIFFERENT DEPTHS IN A DENVER CELL (MINUS 100-MESH GRIND)

for the above three measurements. For the determination of the major elements and the trace elements in the flotation feed and in the tailing products 150-gram (dry basis) pulp samples were withdrawn and dried by evaporation. Mineralogical study samples were prepared by withdrawing a 50-gram (dry basis) pulp sample and screening it wet at 100, 150, 200, 270 and 400 mesh. Since the amounts of the concentrates were rather small (30 to 40 grams), the concentrates from two identical flotation tests were combined, filtered, and the filter cake was split into two portions; one sample was used for the determination of the major elements and the trace elements, and the other for mineralogical study. The fiber count analysis samples were collected in specially cleaned polypropylene containers provided by the Minnesota Department of Health and submitted to the Department's laboratory immediately after the tests in order for the samples to be filtered within 24 hours. The remaining wet samples were sealed in polyester pouches and kept for future use.

A water sample for the determination of trace elements in each feed pulp solution was obtained by centrifuging about 100 milliliters of supernatant solution after a brief settling of about 5 minutes in the flotation cell. The supernantant solutions were placed in 50 milliliter stainless steel tubes and centrifuged at 12,000 rpm for 15 minutes in an International Equipment Company Model HT centrifuge. By applying Stokes' law it was estimated that particles coarser than 0.04 μm were centrifuged out under these conditions. To obtain a water sample from the flotation tailing pulp, about 250 milliliters of supernatant solutions were centrifuged in a similar manner for trace element analyses as well as for residual flotation reagents. The clear solutions thus obtained were used in the

following determinations: 100 milliliters for trace element analyses, 100 milliliters for residual frother determinations, 20 milliliters for residual collector determinations and 20 milliliters for pH determinations.

The effect of aging on water chemical analysis was studied by transferring a rougher tailing pulp to a 2-liter beaker with a minimum of dilution and by obtaining about 250 milliliters of water sample after 1 day, 1 week, and 1 month for the determinations of pH, residual collector and frother, and for trace element analyses in similar manners. To maintain the level of water, after each sampling 250 milliliters of distilled water was added slowly to the pulp so as not to disturb the sediment.

2.3 ANALYTICAL PROCEDURES

2.3.1 Trace Element Analysis

Samples containing one hundred milliliters of centrifuged water for trace element analyses were placed in 125 milliliter polypropylene bottles prepared and supplied by the Minnesota Department of Health through the Regional Copper-Nickel Study. Each bottle contained 1.9 milliliters of 10 to 1 dilution of concentrated ultrex grade nitric acid as the preservative. The water samples and the dried solid samples were delivered to the Regional Copper-Nickel Study for shipment to Barringer Research Ltd. of Toronto, Ontarior, Canada for analysis of elemental composition of the samples.

Analysis samples for dried solids were prepared by first digesting a 250-milligram sample with a mixture of perchloric, nitric and hydrofluoric acids in a teflon beaker at medium heat, evaporating to dryness, redissolving in hydrochloric acid, and diluting to the final volume of

25 milliliters with 0.5N hydrochloric acid. A 32-channel Applied Research Laboratories induction plasma QA-137 optical emission spectrometer was used for analytical determinations. The solution sample was injected into a plasma with temperatures in excess of 10,000° K, where it was atomized and the emission spectra characteristics of the sample atoms present were given off. The emission signals were integrated for 10 seconds, and the analytical results were reported in ppm. The detection limits for various elements reported by Barringer Research Ltd. are shown in Table 5.

TABLE 5. UPPER LIMIT CONCENTRATION (PPM) IMPLIED BY A RESULTS OF N.D. (NOT DETECTED) IN TRACE ELEMENT ANALYSIS DATA BY BARRINGER RESEARCH LIMITED

Au	0.02	Ag	0.002	Cu	0.002
Cd	0.07	Ti	0.001	Mn	0.0005
Fe	0.004	B	0.0017	Ba	0.034
Ni	0.09	As	0.14	Sr	0.0002
Si	0.006	Co	0.016	Zr	0.0014
Zn	0.019	Mg	0.008	Ca	0.025
Al	0.034	K	1.0	B	0.006
Cr	0.007	Na	1.3	Mo	0.03
Pb	0.16	Th	0.06	Se	4.
P	0.7	Be	0.005	Te	3.3
				V	0.0017

2.3.2 Fiber Analysis

Fiber analyses on flotation pulps were made by Mr. Kyle Bishop of the Minnesota Department of Health. Transmission electron microscope samples for fiber count analyses were prepared by filtering a certain volume of each pulp sample submitted by the MRRC as described in Section 2.2 on a Nuclepore filter (0.1 m pore size) so that each TEM grid square resulted in a total count of 5 to 20 fibers. A Hitachi HU12A transmission electron microscope was used for the analysis at 21,000 magnification. Only those particles with a 3-to-1 aspect ratio or greater were counted as fibers, and a total of 40 to 50 fibers were searched and each each fiber characterized with selected area electron diffraction and energy dispersive x-ray analyses. From the volume of pulp sample filtered and the number of fibers per grid square counted, the fiber concentrations were determined. To arrive at the fiber counts of feed, rougher tail (R Tail) and fourth cleaner concentrate (Cl 4 Conc) pulps the dilution factors of 150,100 and 30, respectively, should be applied. The details on the dilution factors are given in Section 2.4.8. The manner in which the fiber counts would vary in flotation was also estimated and given in that section.

2.3.3 Collectors

A number of sulfhydryl collectors, commonly used in the flotation of sulfide minerals, show pronounced light absorption maxima in the near ultraviolet region.[1] Therefore, their concentrations in aqueous pulps can be determined optically. The absorption spectra of some organic compounds are shown in Figure 5 and their absorption maxima as well as their molar extinction coefficients are presented in Table 6. For xanthates, it is reported that, irrespective of chain length, two absorption maxima are observed, one at 301 mμ, and the other at 226 mμ. The molar extinction coefficient of the 301 mμ peak remains constant at 17,500 from methyl to octyl xanthates, whereas the 226 mμ peak shows a gradual increase in wavelength from 225 to 227 mμ and in the extinction coefficient from 8500 to 9500 for these xanthates.

For analytical determination of xanthates in aqueous solutions, the 301 mμ peak is more selective and convenient to use than the 226 mμ peak. The specific extinction coefficient (k) for potassium amyl xanthate (KAX) is calculated through the use of its molecular weight to be 0.0865 when the concentrations are expressed in terms of ppm (c) and the optical density (d) will be related to the concentration in a cuvette with 1.0 cm path length by

$$c = \frac{d}{0.0865} \quad \text{ppm (as KAX)} \qquad \ldots\ldots (2)$$

A Beckman Model DU quartz spectrophotometer was used for the determination of residual xanthate concentrations. Using the above specific extinction coefficient the purity of a commercial potassium amyl xanthate, Dow Z-6, used in the present investigation, was determined to be 69 percent. The

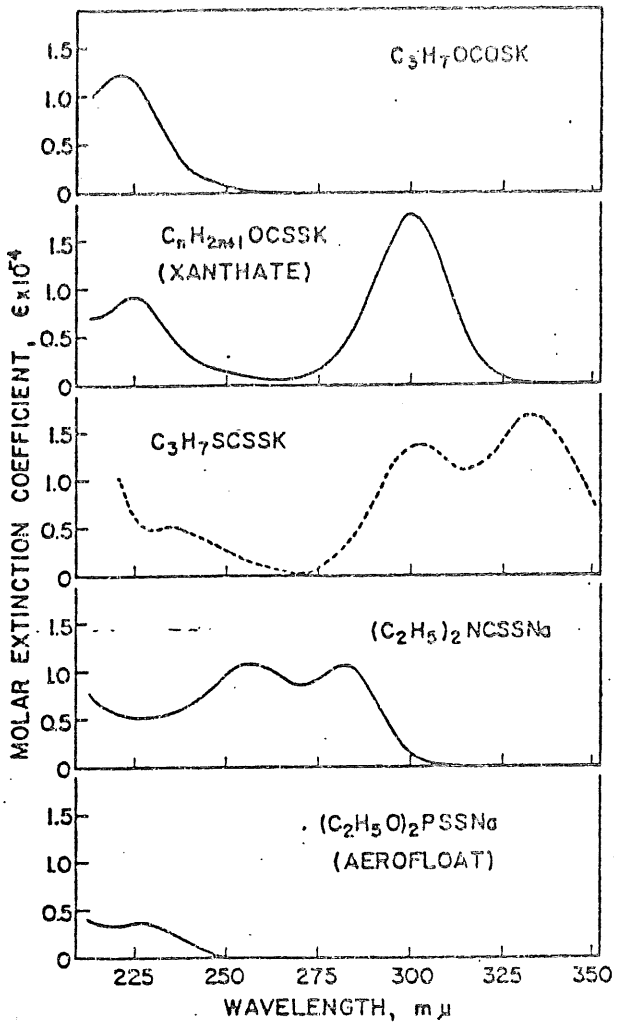


Fig. 5—Absorption spectra of some sulphydryl compounds.

Table 6 Absorption Maxima of Some Sulphydryl Compounds in the 215 to 350-mμ Wavelength

Compounds	n	Absorption Peak, mμ	Slit Width, Mm	ε (Molar Extinction Coefficient)
Monothiocarbonate				
$C_nH_{2n+1}OCOSK$	3	222	0.440	12,400
Dithiocarbonate	1 ~ 8	301	0.360	17,500
$C_nH_{2n+1}OCSSK$ (xanthate)	iso-, 3, 4, 5	226	0.560	8,500-9,500
Trithiocarbonate		~333	0.340	>16,700
$C_nH_{2n+1}SCSSK$	3	~303	0.360	>13,600
		~235	0.510	>5,200
Dithiocarbamate $(C_nH_{2n+1})_2NCSSNa$	2	282.5	0.390	10,500
		257.5	0.420	10,700
Dithiophosphate $(C_nH_{2n+1}O)_2PSSNa$ (aerofloat)	2	227	0.560	3,700
Mercaptan $C_nH_{2n+1}SH$	3	No peak	—	—

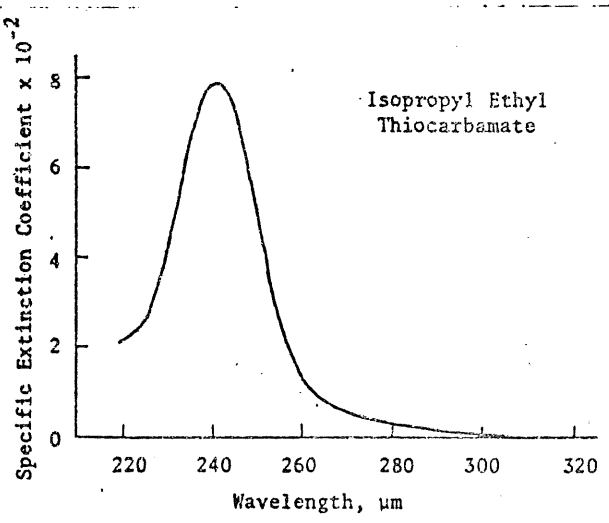


FIGURE 6. ABSORPTION SPECTRUM OF ISOPROPYL ETHYL THIOCARBAMATE (DOW Z-200)

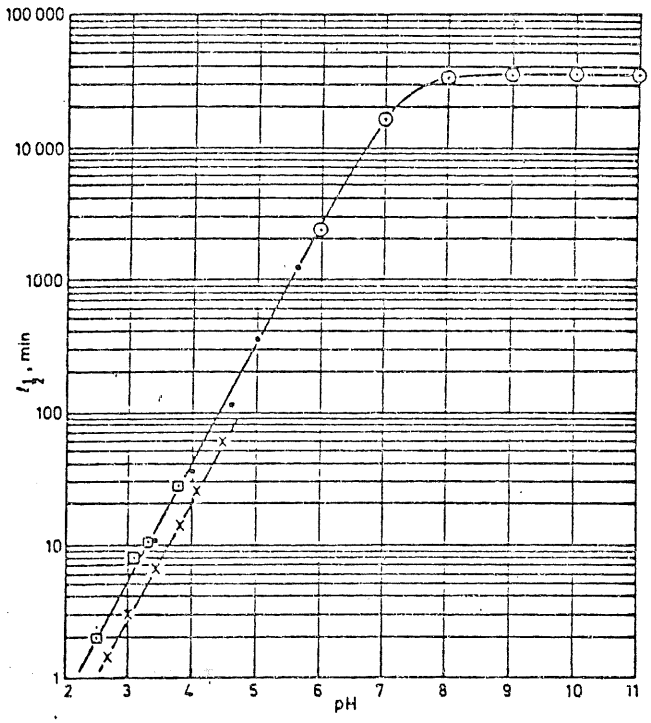


Fig. 7 Variation of half-life of decomposition of xanthate with pH: ⊡ Allison and Finkelstein[88] (25°C); × Iwasaki and Cooke[79] (23·5°C); ● Homylev[201] (25°C); ⊙ Finkelstein [82] (25°C)

detection limit for the xanthate in pulp solutions is estimated to be about 0.1 ppm.

In the differential flotation of a copper-nickel sample isopropyl ethyl thiocarbamate (Dow Z-200) was used as a collector. The absorption spectrum of isopropyl ethyl thiocarbamate is given in Figure 6. Only one light absorption maximum was observed for this collector at 241 mμ with the specific extinction coefficient of 0.079. Hence the optical density may be related to the concentration in a cuvette with a 1.0 cm path length by

$$c = \frac{d}{0.079} \quad \text{ppm (as isopropyl ethyl thiocarbamate)} \quad . \; . \; (3)$$

The stability of xanthates in flotation pulp solutions becomes of interest not only for analytical determinations of their residual concentrations, but also for the possibility of their degradation in tailing ponds. Xanthates are known to be unstable in aqueous solutions and below pH 8 the rate of their decomposition depends strongly on pH, according to

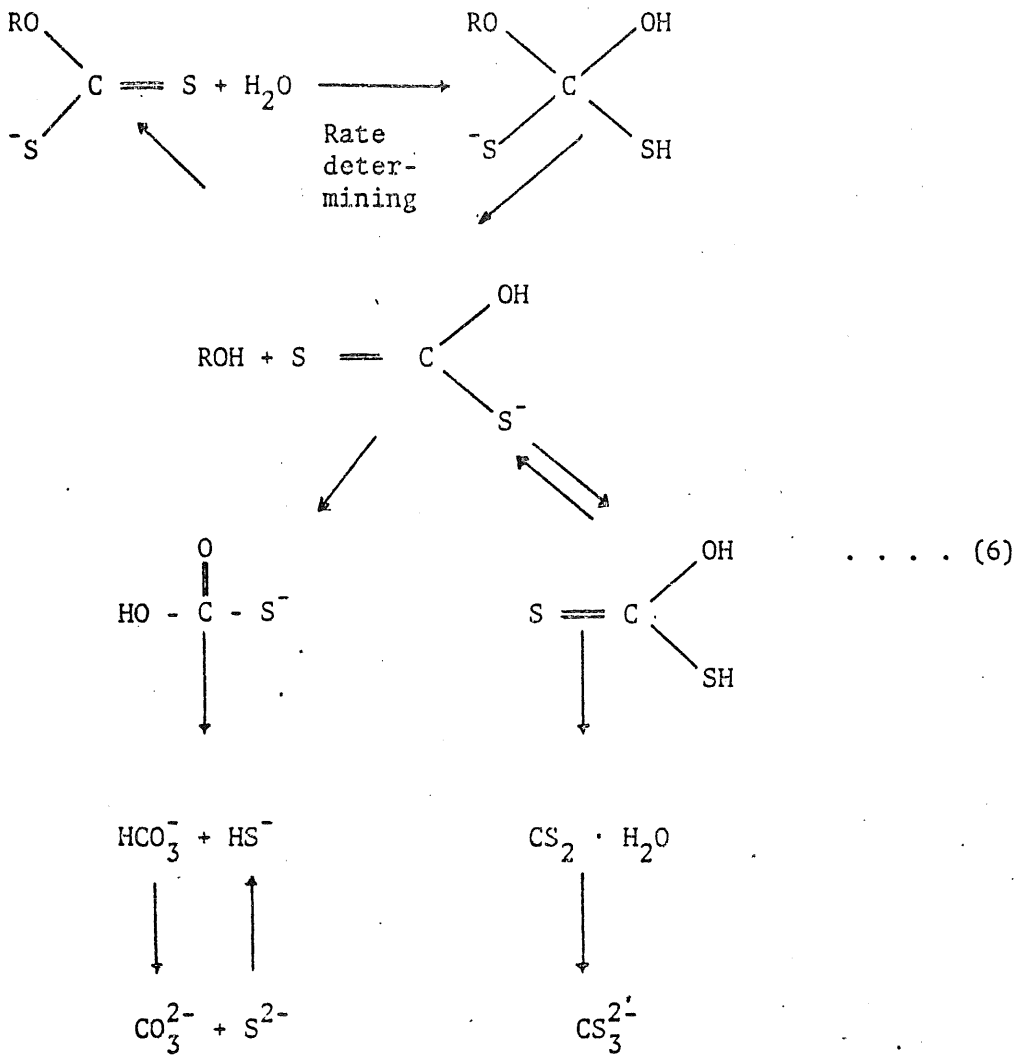
$$H^+ + X^- \rightleftharpoons HX \rightarrow ROH + CS_2 \quad . \; . \; . \; . \; (4)$$

In the alkaline range up to pH 12 the rate is known to be virtually independent of pH and the decomposition reaction considered to be most probable is the oxidation of xanthate to dixanthogen

$$2X^- + H_2O + 1/2\ O_2 \rightarrow X_2 + 2OH^- \quad . \; . \; . \; . \; (5)$$

Figure 7 shows the dependence of decomposition rate of ethyl xanthate with pH,[2] and a similar behavior may be expected of amyl xanthate. The eventual fate of the above products of decomposition, particularly in neutral and alkaline ranges, becomes of interest in the present project. Rao[3] summarized the mechanism suggested by Philipp and Fichte[4] involving the formation of

monothiocarbonate as an intermediate product in the decomposition of xanthate in alkaline medium as follows:



. . . . (6)

The thiocarbonate may then split into sulfide and carbon disulfide, which in turn would hydrolyze into carbonate and sulfide, according to

$$CS_2 + 6OH^- \rightarrow CO_3^{2-} + 2S^{2-} + 3H_2O \quad . . . . (7)$$

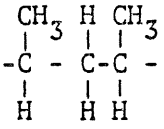
Two series of preliminary tests were performed on flotation pulp solutions. In one series a flotation test was carried out using 0.1 pound of KAX per ton and in another series using 0.05 pound of KAX per ton (see Section 2.5.3).

The rougher tailing pulps were centrifuged and the clear solutions were split into three aliquot portions, approximately 250 milliliters each. One portion was kept in a glass-stoppered volumetric flask, a second portion in an open beaker, and the third portion in an open beaker with air bubbling through the solution. The optical densities were determined daily over several days. The results are plotted in Figure 8.

It is apparent in the figure that the collector was indeed unstable although the solution pH ranged from 7.5 to 8.6, and that the solutions exposed to air or aerated decomposed most rapidly, implying the role played by oxygen. It appeared, therefore, that the analytical samples may be kept for a few hours without seriously affecting the readings if dissolved oxygen is kept to a minimum and perhaps if solution samples are kept refrigerated in order to further slow the decomposition reaction.

2.3.4 Frothers

Methyl isobutyl carbinol (MIBC), having the following structural formula,



was used as a frother in the present investigation. Since the range of its residual concentrations in pulp solution is too low to be determined directly in a gas chromatograph, a special procedure involving dichloremethane extraction prior to gas chromatographic analyses was developed by Professor Gary A. Reineccius of the Department of Food Science and Nutrition of the University of Minnesota, and the analyses were carried out by Mr. Wayne R. Peterson in his laboratory.

The extraction procedure was as follows. Seventy-five milliliters of the centrifuged pulp solution was placed in a separatory funnel and 5 milliliters

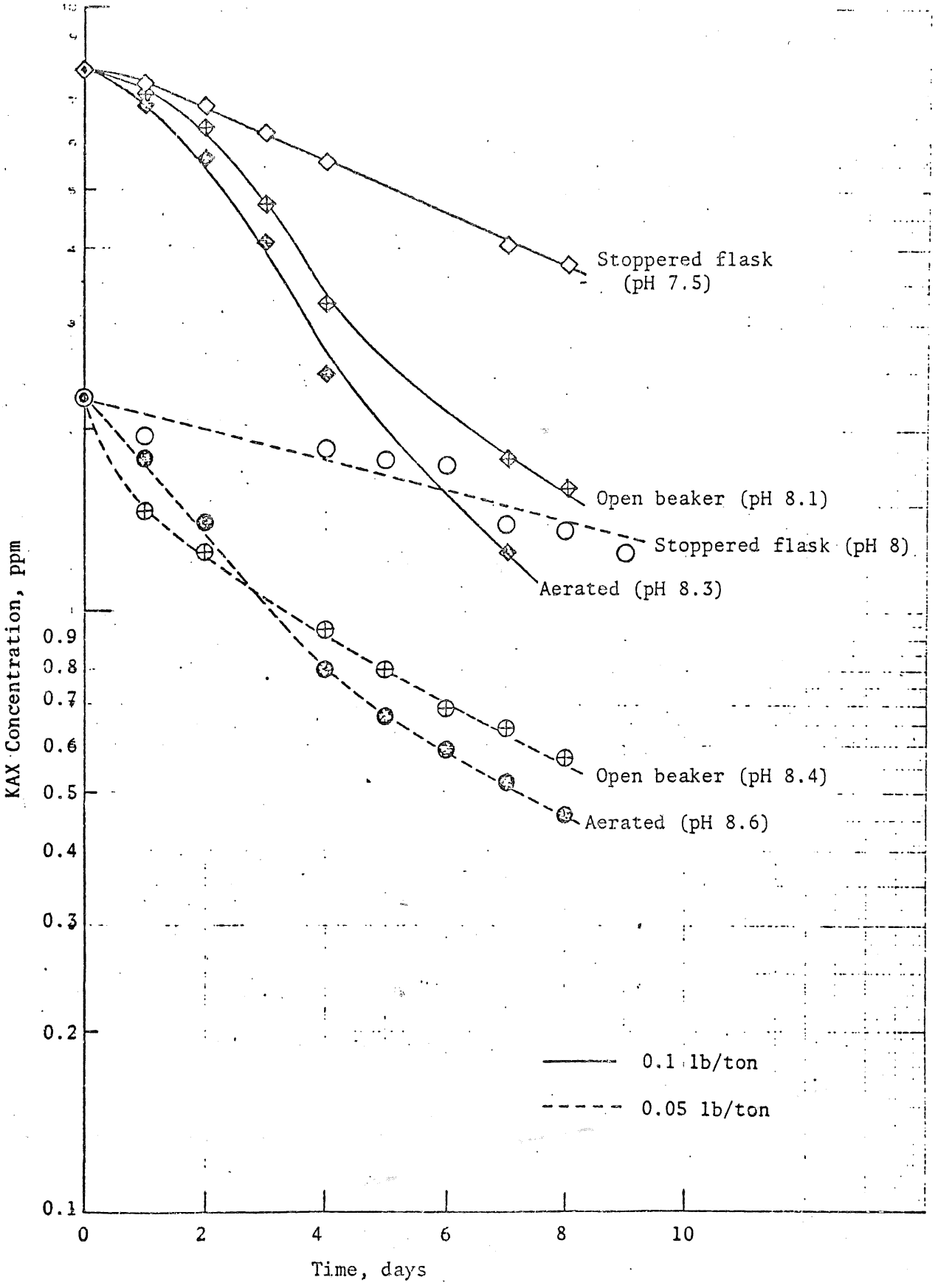


FIGURE 8. DECOMPOSITION OF KAX IN FLOTATION PULP SOLUTION AS A FUNCTION OF TIME

of an internal standard solution (60 μg n-hexanol per gram solution) was added. Ten milliliters of dichloromethane was used to extract the alcohols from the aqueous solution. This extraction procedure was repeated five times. Then the resulting dichloromethane solutions (50 milliliter total) were pooled, and 0.5 grams of anhydrous magnesium sulfate was added and the mixture was agitated for 30 minutes to remove water. The volume of dichloromethane solution was reduced by evaporation on a steam bath to one milliliter, and the concentrated solution was analyzed using a Hewlett-Packard 5830 gas chromatograph with a flame ionization detector. A 10-foot column packed with Carbowax 20M was held at 155°C and helium was used as the carrier gas at a flow rate of 32 milliliters per minute. The MIBC contents were determined relative to the amount of n-hexanol added as an internal standard.

Since a time lapse of a few days between the flotation tests and the analyses was inevitable, the stability of MIBC in the relevant concentration range was tested on a few standard solutions prepared two weeks apart. The analytical results were virtually identical indicating that MIBC in aqueous solutions was quite stable over a two week period if the solutions were kept in ground-glass stopeered flasks. To further confirm the stability of MIBC, a pulp solution after a flotation test was analyzed immediately and again, in 10 days, after keeping the pulp solution samples in two separate ground-glass stoppered flasks, one at room temperature and another in a refrigerator. The MIBC concentrations were, respectively, 5.02, 4.76 and 4.62 ppm. It appears, therefore, that by keeping the centrifuged pulp solutions in stoppered flasks the decomposition of MIBC could be minimized. This particular point is an advantage for analytical purposes.

As will be shown later, MIBC could be decomposed measurably in air-exposed pulps over a week-long period and almost completely over a month-long period.

2.3.5 Size Distributions

For the determination of size distributions in the 'subsieve' range, the Andreasen pipette method[5] was used. This method defines the size of particles in a pulp according to their settling velocity in a fluid. When water is used as a sedimenting medium and minerals of common specific gravities are investigated, determinations of particle size fineness ranging from 30 to 0.3 μm can be made.

The Andreasen pipette, as shown in Figure 9, consists of a glass cyclinder about 6 cm in diameter, having a capacity of approximately 550 milliliters (W) and a pipette (P) connected to a 10-milliliter reservoir by means of a three-way stopcock. The ground glass stopper has a small vent (L) to let in air when samples are being withdrawn. The stem of the pipette ends at the level of the zero mark, so that the settling depth, from the top of the suspension to the tip of the pipette, is read directly on the engraved scale.

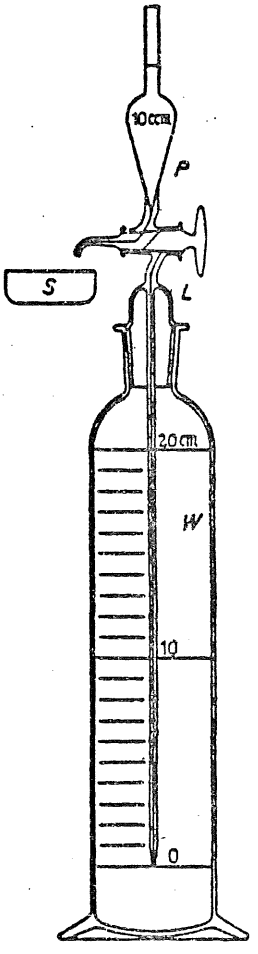


Fig. 9 — Andreasen Pipette for Measuring Size Distribution

A pulp sample containing approximately 10 grams was added to the sedimentation cylinder together with dispersants and diluted exactly to the 20-cm level with the pipette in place, and the suspension was thoroughly mixed by repeated inversions. Suspensions of feed and tailing pulps in distilled water were observed to be dispersed without the use of dispersants. Samples of the suspension, 10 milliliters in volume, were withdrawn

at 1, 2, 4, 8, 16, 32, and 64 minutes, dried and weighed. The concentration of solid particles at the start of settling (C_o) was calculated by summing the weights of all the samples used in a test and the volume of the suspension. After settling for time (t), the concentration of solids (C_t) measured at depth (s) is the same as the total original concentration of all particles whose settling velocities are less than s/t. Thus, 100 C_t/C_o is the cumulative percent weight finer than the size corresponding to settling velocity s/t.

Size distributions were determined on the feed and products (concentrate, rougher, and first cleaner tailing) of a flotation test carried out under conditions of a minus 200-mesh grind with reagent levels of 0.05 pound of KAX and 0.05 pound of MIBC per ton. Based on the weights of the flotation products, a 15-milliliter sample of the feed and a 20-milliliter sample of the rougher tailing pulp were taken directly from a 2-liter Denver cell by siphoning and by pipetting for a check on the sampling methods. The first cleaner tailing (Cl 1 Tail) sample was obtained by siphoning 100 milliliters of the pulp. The cleaner concentrate (Cl 4 Conc) samples were obtained after destroying the froth by adding equal volume of denatured alcohol with water in the Denver cell. The concentrate was confirmed to have no tendency to float by turning on the air and two 200-milliliterliter samples of the pulp were taken by siphoning.

Since the feed, the rougher and the first cleaner tailing samples were dispersed in distilled water, their size distributions were determined without adding any dispersants to the suspension. The pertinent test conditions and the results are presented in Table 7 and the Schuhmann plots of these data in Figure 10. To check if the addition of dispersants indeed

TABLE 7. ANDREASEN PIPET SIZING RESULTS ON FLOTATION FEED, CONCENTRATE AND TAILING SAMPLES
(FLOTATION CONDITIONS: MINUS 200 MESH GRIND, 0.05 LB PER TON KAX, 0.05 LB PER TON MIBC)

	Feed			R Tail		Cl Tail	Concentrate**
	Siphoned	Siphoned*	Pipetted	Siphoned	Pipetted	Siphoned	Siphoned
Sample Weight, grams	15.50	9.88	15.47	13.10	13.39	10.56	9.91
Sp.Gr. of Particle	3.05	2.95	3.05	2.95	2.95	2.94	3.56
Temp of Medium, °C	25.2	28.3	25.2	25.2	25.2	27.0	26.7
Sp.Gr. of Medium	0.9970	0.9962	0.9970	0.9970	0.9970	0.9965	0.928**
Viscosity of Medium, cp	0.8897	0.8306	0.8897	0.8897	0.8897	0.8545	2.4229**

Sampling Time, Minutes	Feed						R Tail				Cl Tail		Concentrate**	
	Siphoned		Siphoned*		Pipetted		Siphoned		Pipetted		Siphoned		Siphoned	
	Particle dia., μm	Cum % Wt	Particle dia., μm	Cum % Wt	Particle dia., μm	Cum % Wt	Particle dia., μm	Cum % Wt	Particle dia., μm	Cum % Wt	Particle dia., μm	Cum % Wt	Particle dia., μm	Cum % Wt
1	51.4	67.2	51.0	67.3	51.4	55.0	52.8	61.8	52.8	62.9	51.5	97.4	75.1	90.8
2	36.0	47.2	35.7	49.8	36.0	52.4	36.9	45.2	36.9	44.9	36.0	85.8	52.6	76.1
4	25.2	32.5	25.0	31.8	25.2	33.0	25.9	27.1	25.9	25.2	25.2	57.7	36.8	53.6
8	17.6	21.8	17.5	25.5	17.6	16.5	18.1	17.9	18.1	12.0	17.6	28.4	25.8	37.7
16	12.3	14.8	12.2	17.2	12.3	10.9	12.7	11.4	12.7	8.6	12.3	20.5	18.0	26.5
32	8.6	10.8	8.6	12.4	8.6	8.3	8.9	7.8	8.9	8.3	8.6	15.8	12.5	18.2
64	6.0	8.1	6.0	8.7	6.0	6.3	6.2	6.1	6.2	5.2	6.0	11.6	8.2	10.5

* A combination of 0.1 gram caustic soda and 0.1 gram quebracho used as dispersant.
** An equivolume mixture of denatured alcohol and distilled water used as the sedimentation liquid, and a combination of 0.2 gram sodium sulfide and 0.3 gram quebracho used as dispersant.

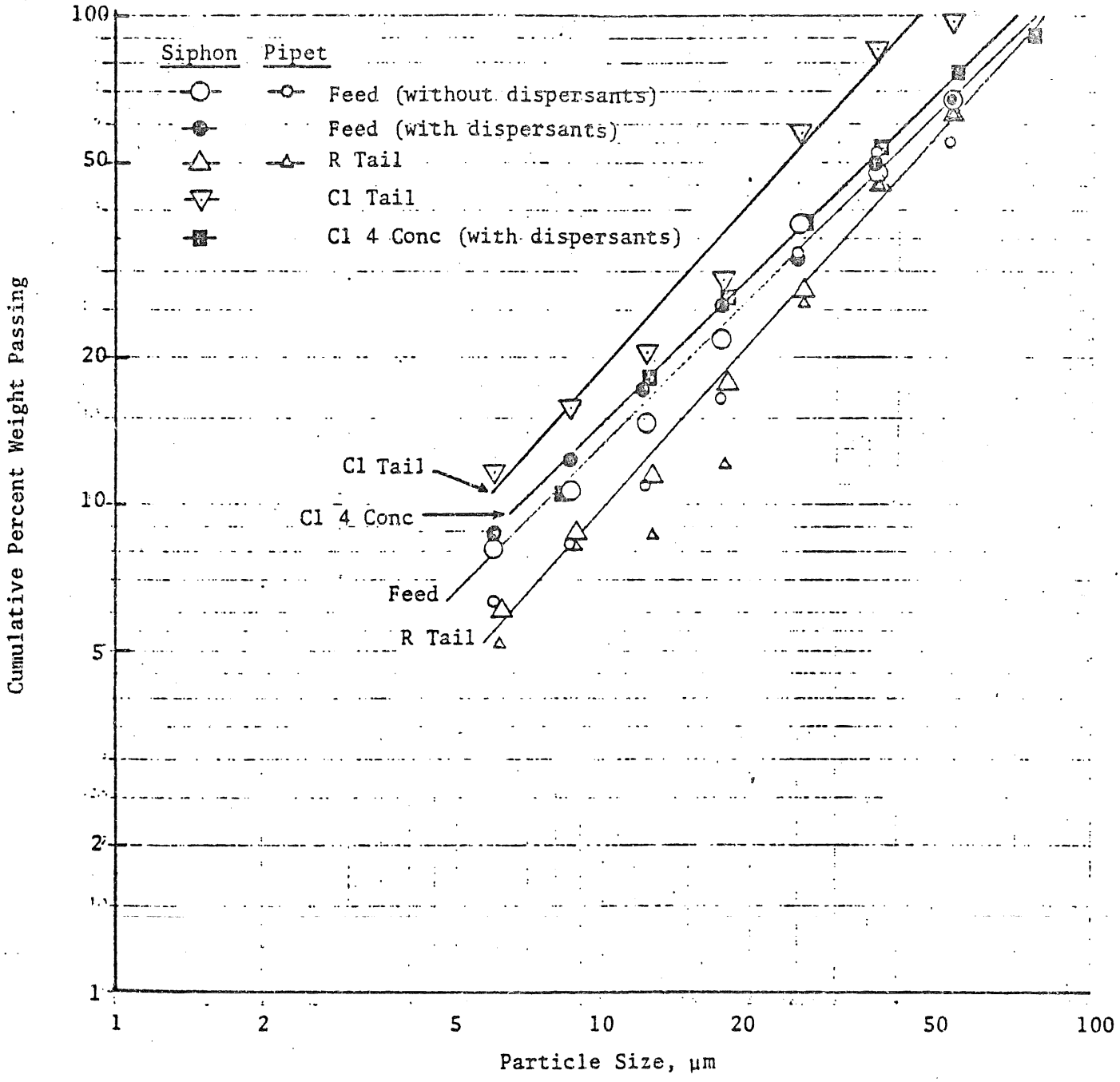


FIGURE 10. SIZE DISTRIUBTIONS OF FLOTATION FEED, CONCENTRATE AND TAILING SAMPLES (MINUS 200 MESH GRIND)

would not affect the test results, 0.1 gram of sodium hydroxide and 0.1 gram of quebracho, a combination commonly used in the Andreasen pipette method for size determinations of ground quartz, were added in a suspension of a rougher tailing sample and the size distributions were determined. The pH of the suspension was 12. The cleaner concentrate (Cl 4 Conc) was noted to be flocculated and after a few preliminary tests it was decided that a combination of 0.2 gram of sodium sulfide and 0.3 gram of quebracho gave adequate dispersion. The pH of the suspension was 11.5. All of the results are included in Table 7 and Figure 10.

In the figure it is apparent that the two sampling techniques, namely siphoning and pipetting, gave virtually identical results, and that the results with the dispersants were identical to those without dispersants. It is also noted that the size distribution of R Tail is coarser than that of feed and the size distributions of Cl 4 Conc and Cl 1 Tail are finer than that of the feed.

As the test program on individual samples progressed, it became evident that certain cleaner concentrates containing notable amounts of magnetic pyrrhotite particles could not be fully dispersed with sodium sulfide and quebracho even when the amounts of the dispersants added were doubled, tripled, or quadrupled. Demagnetizing of samples through a 400-cycle a.c. coil prior to dispersant addition did not help in deflocculating the suspension. Microscreening had to be used for the determination of the size distributions of the cleaner concentrates (Cl 4 Conc) (see Section 2.3.6).

In the determination of size distributions of feed and tailing samples by the Andreasen pipet method, it was decided to use a combination of caustic soda and quebracho as dispersants to insure full dispersion of

suspensions even though the feed and tailing samples appeared to be adequately dispersed in distilled water. In this manner the results of size fractionation (see Section 2.3.6) may be checked since the sedimentation sizing method was used to fractionate feed and rougher tailing samples without dispersants. These fractionated samples are to be dried by evaporation for trace element analyses and it is desirable to refrain from using any additions to these samples.

2.3.6 Size Fractionation

Initially an attempt was made to separate the flotation products into individual size fractions in the 'subsieve' range with microscreens with openings of 20, 10, 5 and 2 μm. The extremely long time required to screen at 5 and 2 μm caused corrosion pitting of screen surfaces due presumably to sulfuric acid formed by the oxidation of sulfide minerals. Hence the sedimentation and decantation method[5] was tested. The apparatus consisted of a 1000-milliliter graduated cylinder and a siphon with a turned-up intake. The open end of the siphon cleared the bottom of the cylinder by about 1.5 inches so that introducing it and withdrawing liquid did not disturb the sediment.

A pulp sample containing approximately 10 grams was added to the sedimentation cyclinder with sufficient distilled water to bring the level to the 500-milliliter mark. The suspension was mixed thoroughly by inversion and then allowed to settle for the prescribed settling time before being decanted with the siphon. The sediment was resuspended, and the process repeated three times using the same settling times. The minus 5-μm fraction was removed first. Then the settling time was halved and the next fractions

(5/10 μm followed by 10/20 μm) were taken off. The results of size fractionation on a minus 200-mesh grind sample using microscreening and sedimentation sizing are presented in Table 8 and the Schuhmann plots of these data in Figure 11 together with the results of the Andreasen pipette method. It is readily apparent that all three fractionation methods were in good agreement.

TABLE 8. COMPARISON OF SIZE FRACTIONATION RESULTS ON A MINUS 200 MESH FEED SAMPLE USING MICROSCREENING AND SEDIMENTATION SIZING

Size, μm	% Weight	
	Micro-screen	Sedimen-tation
+20	74.6	77.8
+10	11.6	9.7
+5	8.8	5.3
-5	5.0	7.2

The photomicrographs of size fractions, 20/10 and 10/5 μm, by microscreening and sedimentation sizing are shown in Figure 12. It is to be noted in the photographs that the sized products by these methods are in good agreement with the defined sizes and that the products by the microscreening method contain more very fine particles than those by the sedimentation sizing method. The presence of fines might be attributable to insufficient screening.

Cleaner concentrates in equivolume mixtures of water and alcohol, however, were flocculated and the use of a dispersant was necessary in the sedimentation sizing. A combination of 0.2 gram of sodium sulfide and 0.3 gram of quebracho was found to be effective as a dispersant. To

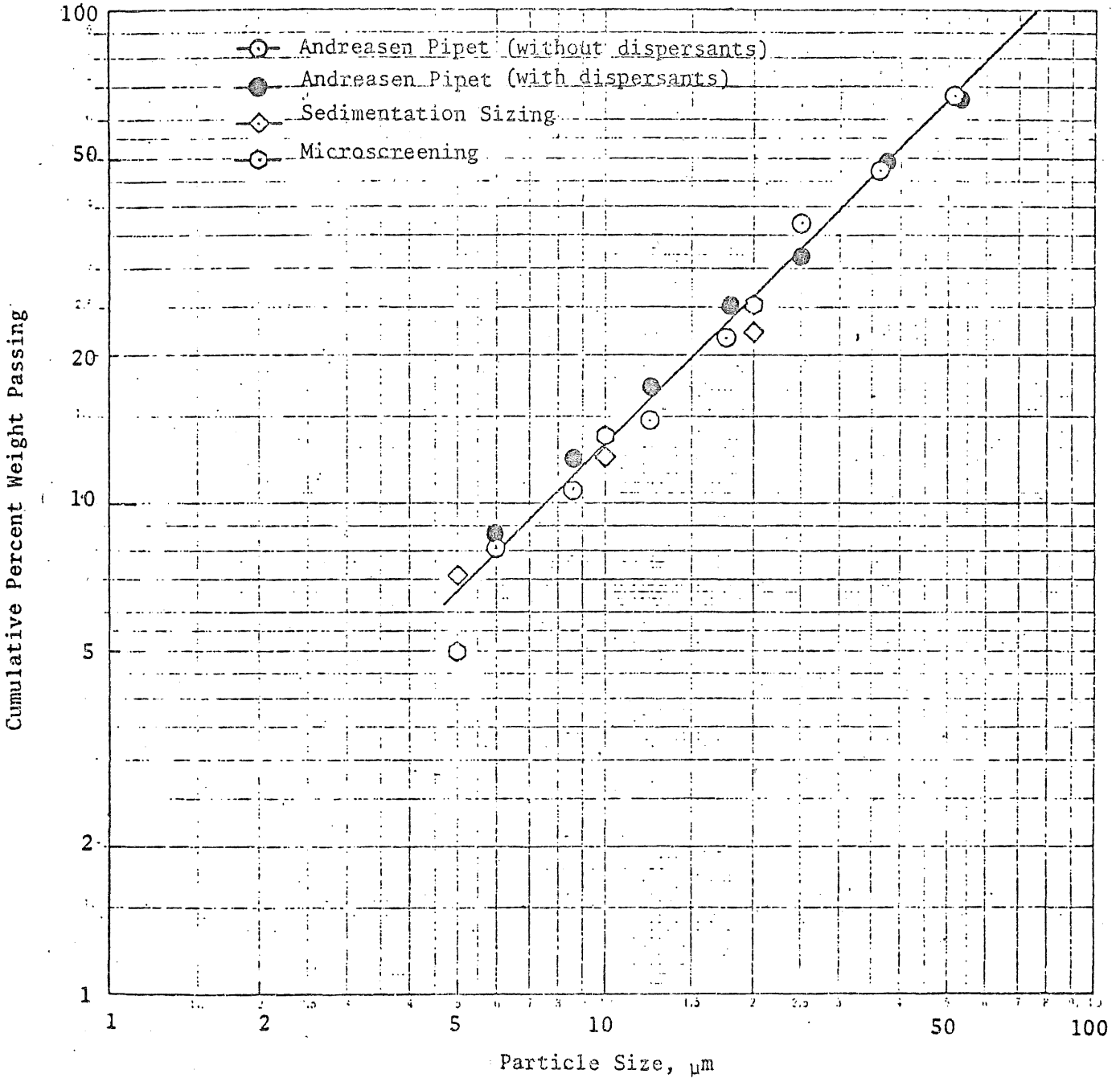
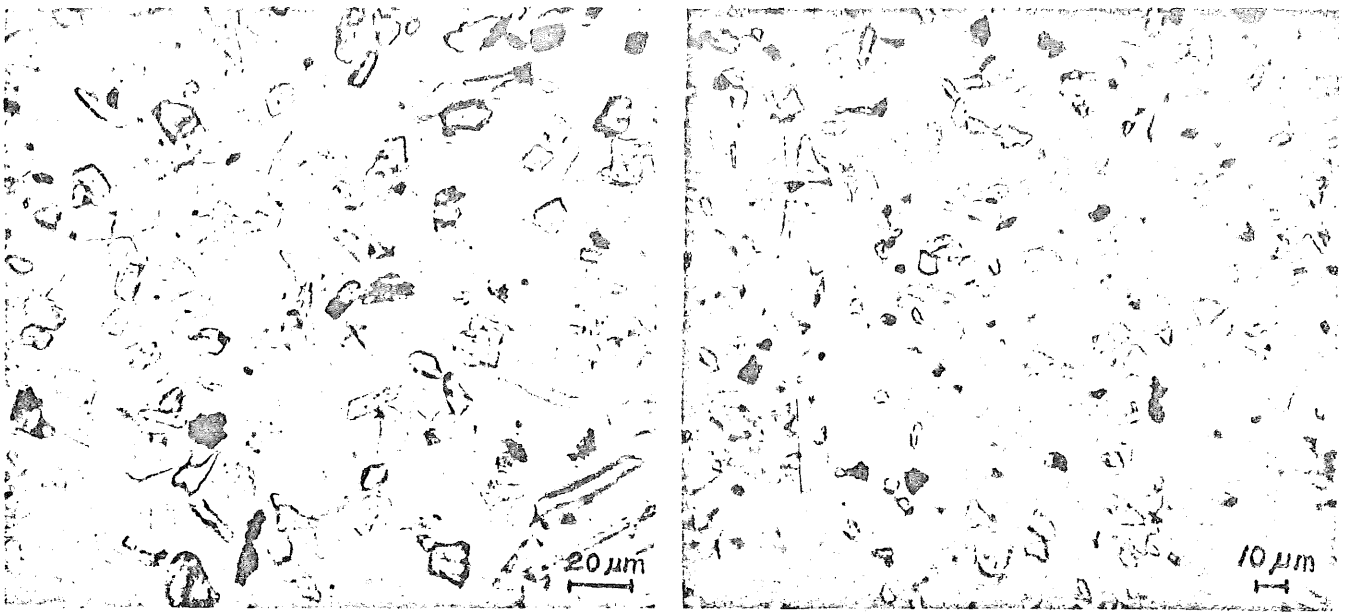


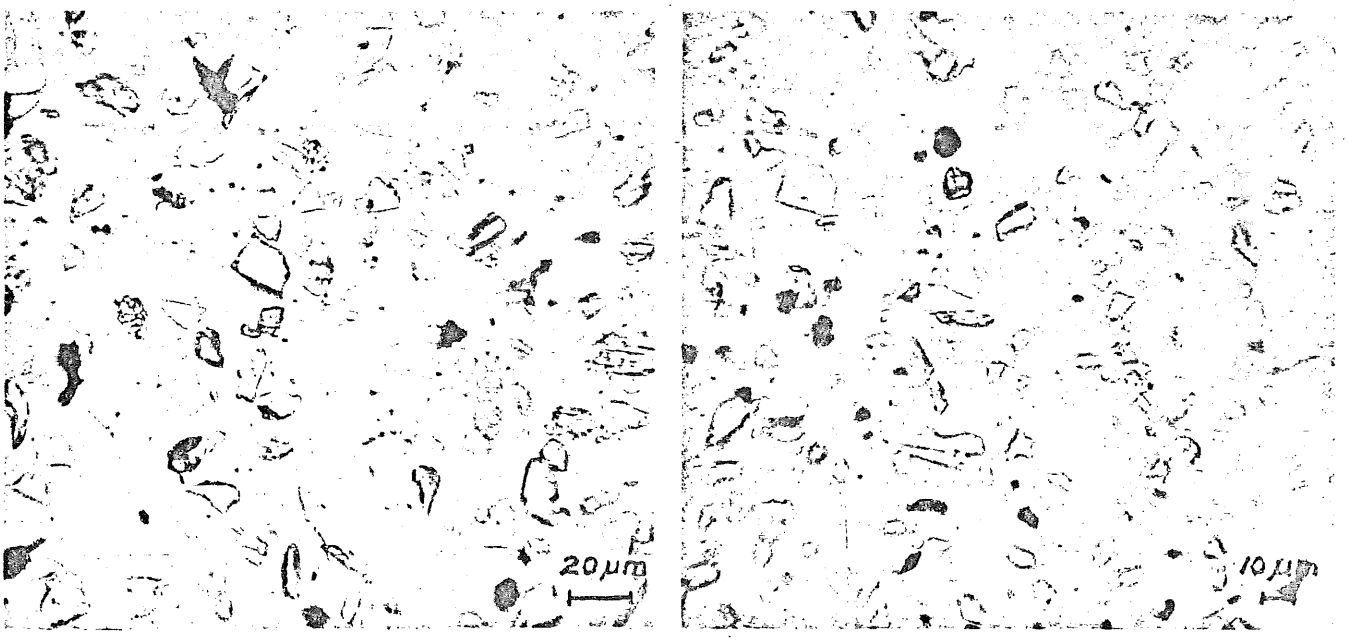
FIGURE 11. COMPARISON OF SIZE DISTRIBUTIONS OF A MINUS 200 MESH FEED SAMPLE DETERMINED BY THREE DIFFERENT METHODS



20/10 µm Fraction

10/5 µm Fraction

(a) Sedimentation Sizing



20/10 µm Fraction

10/5 µm Fraction

(b) Microscreening

FIGURE 12. PHOTOMICROGRAPHS OF SIZED FRACTIONS OF A MINUS 200 MESH FEED SAMPLE USING SIZING AND MICROSCREENING METHODS

ascertain if the sedimentation method could be used to fractionate a cleaner concentrate, a sample of AX9002 C1 4 Conc was used. The dispersants were used in each decantation to insure dispersion. Then each fraction was centrifuged (15 minutes at 12,000 rpm) to remove the dispersant that remained in the supernatant solution. The centrifuged solids were resuspended with distilled water and again centrifuged. This process of washing was repeated four times after which the supernatant solution became virtually colorless. The solid samples were then dried and weighed. The results are plotted in Figure 13 together with those of the Andreasen pipette method.

To further check the above results another sample of AX9002 C1 4 Conc was fractionated by microscreening. The sample was screened wet first on a 37-μm screen, then its undersize on a 20-μm screen and finally on a 10-μm screen. The screening on a 5-μm screen required an unduly long time and this screening step was discontinued not only in the interest of time, but also for fear that the screen might again be corroded to form pit holes. As shown in Figure 13 the results agreed well with those of the sedimentation sizing and the Andreasen pipette methods in the presence of dispersants.

When a similar set of tests was made on the US9001 sample which contained a notable amount of magnetic pyrrhotite, the results of the Andreasen pipette method in the presence of dispersants were markedly different from those of microscreening (see Figure 14).

Hence, it was decided that the size fractionation of feed and rougher tailing samples was to be carried out by the sedimentation sizing method without dispersant to 5 μm so that the trace element analysis results would not be disturbed, and that the size fractionation of cleaner concentrate samples was to be done by microscreening to 10 μm.

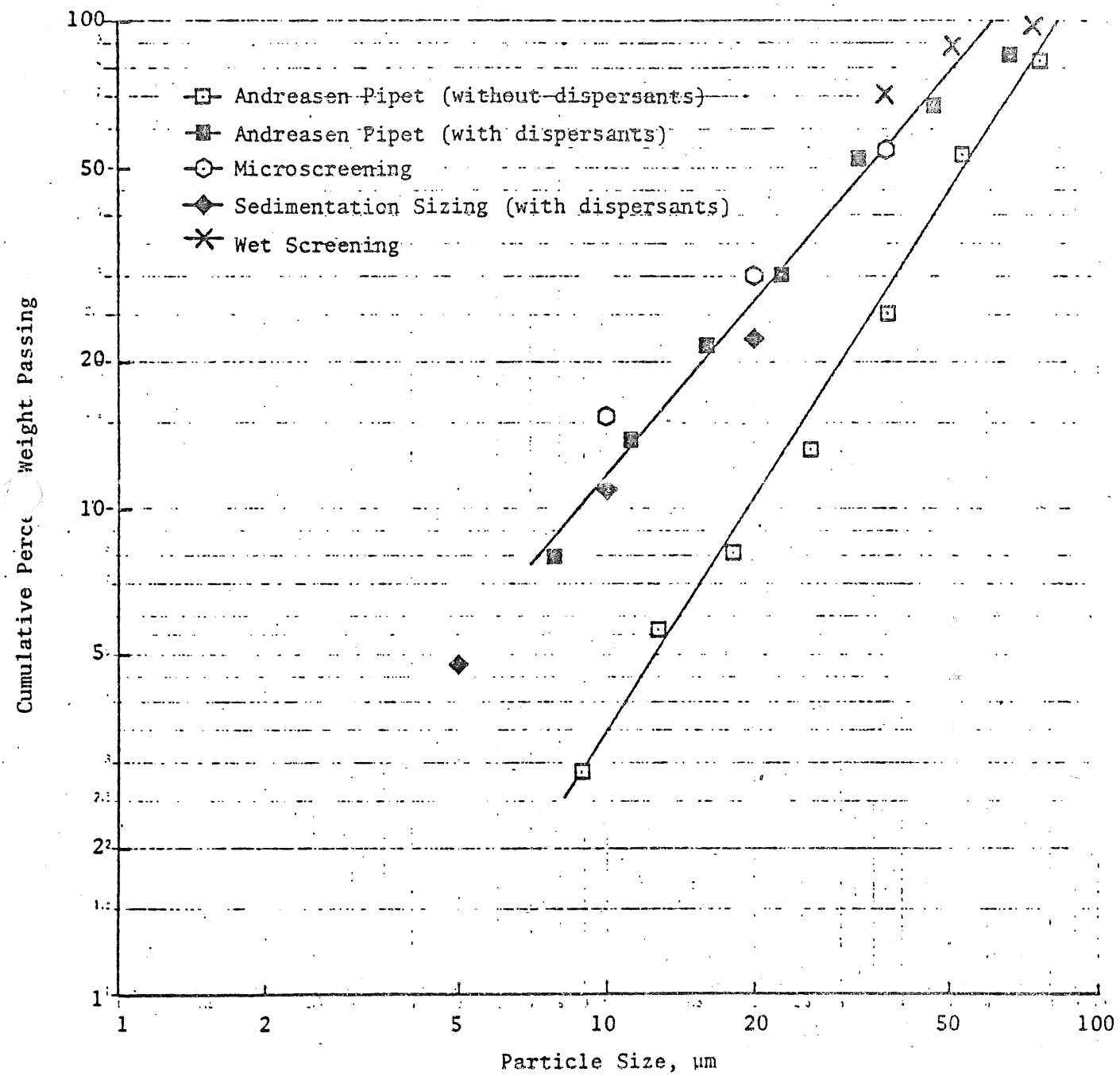


FIGURE 13. COMPARISON OF SIZE DISTRIBUTIONS OF A MINUS 200 MESH CLEANER CONCENTRATE SAMPLE OF AX9002 DETERMINED BY ANDREASEN PIPETTE SEDIMENTATION SIZING AND MICROSCREENING METHODS

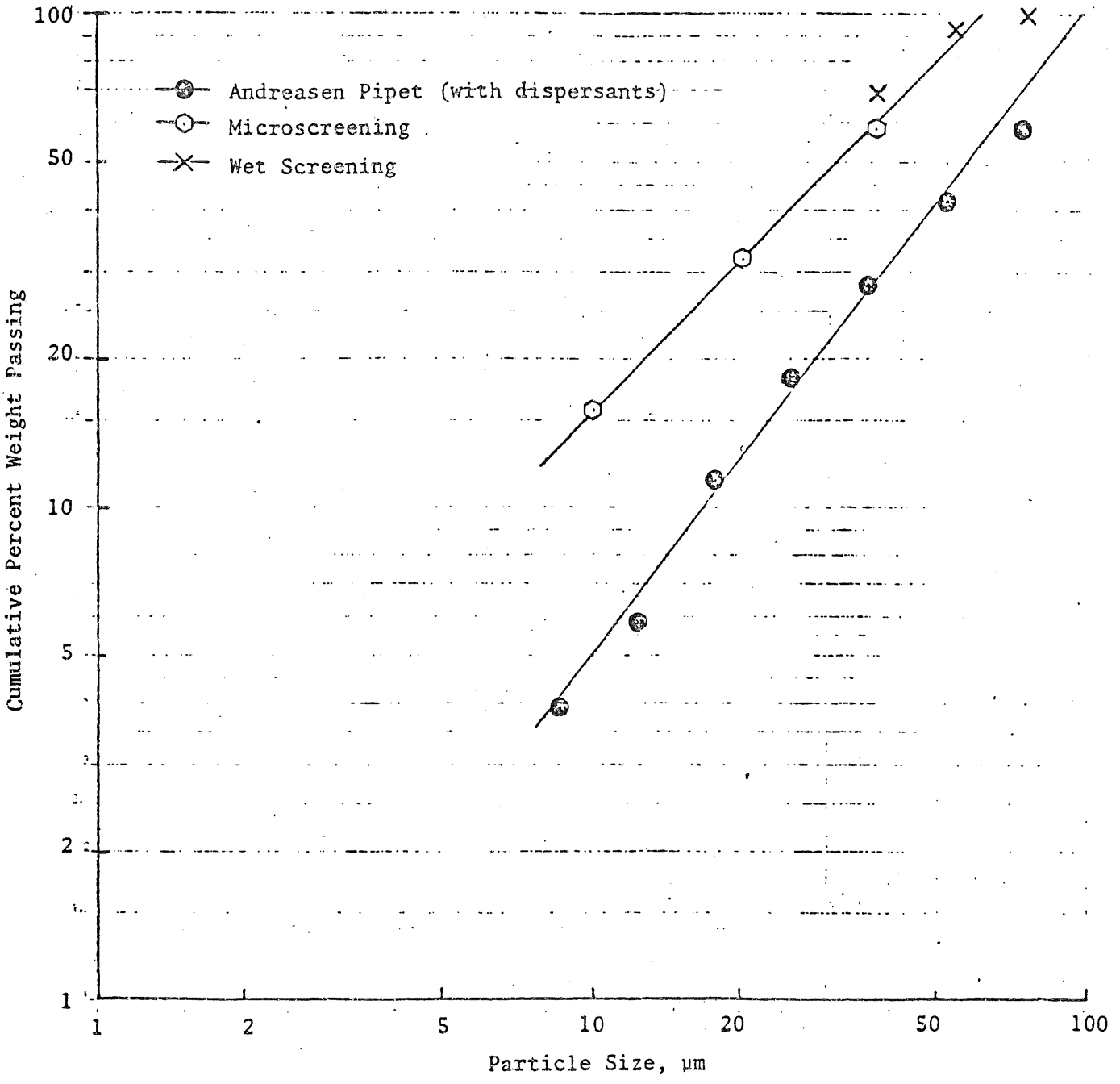


FIGURE 14. COMPARISON OF SIZE DISTRIBUTIONS OF A MINUS 200 MESH CLEANER CONCENTRATE SAMPLE OF US9001 DETERMINED BY ANDREASEN PIPETTE AND MICROSCREENING METHODS

2.4 FLOTATION TEST PROCEDURE

A limited number of flotation tests were carried out to develop a standardized procedure that could be used to study the environmental implications on a number of samples made available from the region. The effects of the mesh-of-grind and the levels of collector and frother additions on the residual sulfide contents in tailings and the effect of repeated cleaner flotation on the grade of concentrates were investigated. Two flowsheets were proposed to be used in the present investigation. The first was a metallurgically simple flowsheet involving grinding to minus 200 mesh followed by flotation (referred to as 'One-stage Grind Flotation' in this report). The second was a more complex flowsheet involving coarse grinding to minus 65 mesh followed by flotation and then by regrinding of the flotation concentrate to minus 270 mesh and reflotation (referred to as 'Two-stage Grind Flotation'). The latter flowsheet is expected to require less energy and also assumed to generate less fibrous particles during grinding. The flowsheets of these two flotation procedures are given in Figures 15 and 16. The details of the effects of each parameter on the flotation results that led to the development of the proposed flowsheets are presented in the following sections.

2.4.1 Preliminary Flotation Tests

In previous investigations[6,7] a Fagergren laboratory flotation cell was used, but the coarse, heavy particles tended to settle at the bottom of the cell. With a Denver laboratory flotation cell, equipped with a special plastic collar around the impeller shaft for more efficient circulation of the pulp, no settling of coarse, heavy particles was observed. Hence a

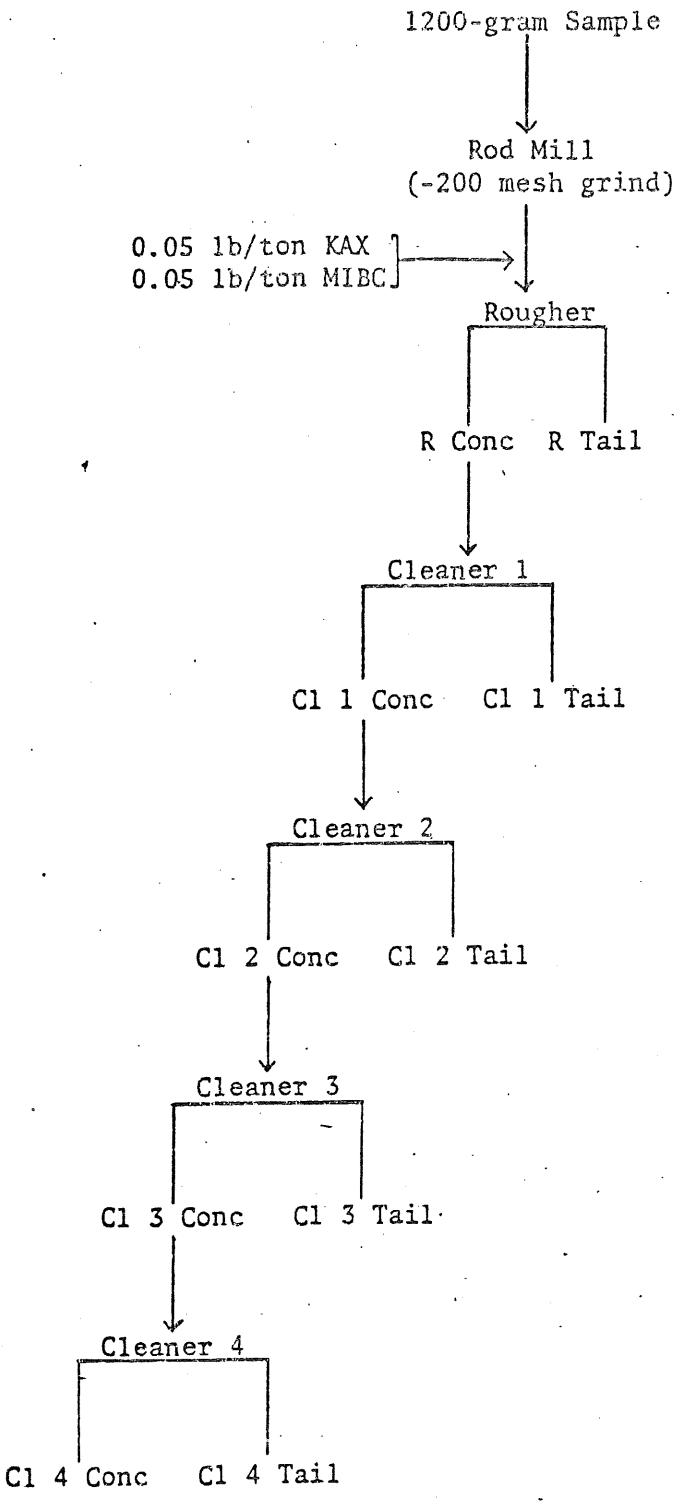


FIGURE 15. FLOWSHEET OF ONE-STAGE GRIND FLOTATION TESTS

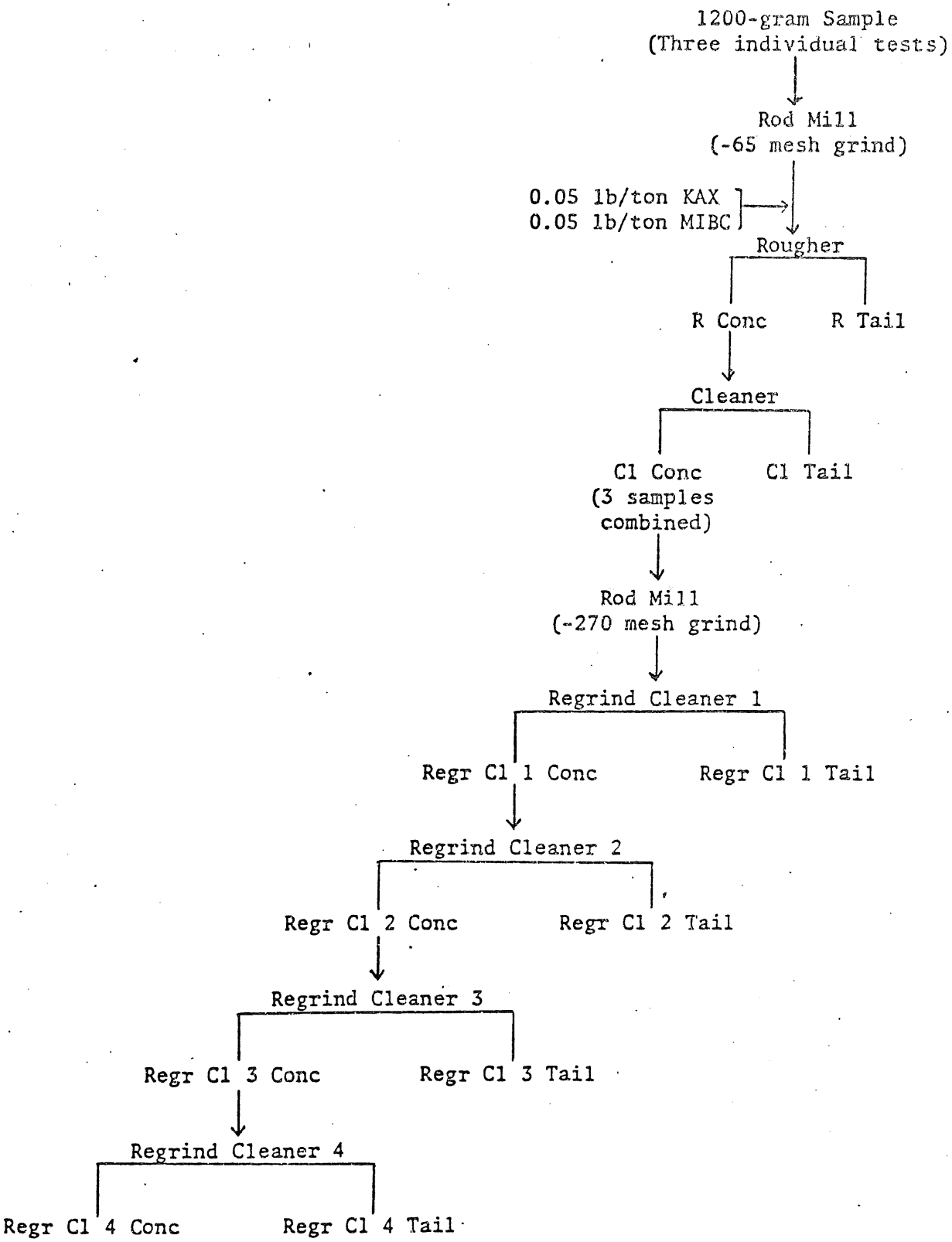


FIGURE 16. FLOWSHEET OF TWO-STAGE GRIND FLOTATION TESTS

Denver cell was used to test the effects of percent solids, sample weight and flotation time. In this series of tests either a 600-gram or a 1200-gram sample was ground nominally to minus 200 mesh, conditioned with 0.05 pound of potassium amyl xanthate per ton for 2 minutes and then with 0.05 pound (2 drops) of MIBC per ton for one minute. The pulp pH at this point ranged from 9 to 9.3. The air valve was then opened and the rougher froth collected for either 5 or 10 minutes. The rougher concentrate was then returned to the cell and cleaned once or twice. The flotation time in cleaning was fixed at 3 minutes. The test conditions and the flotation results are given in Table 9.

The test results are seen to be essentailly independent of these three parameters although higher percent solids appear to result in higher weight recoveries at lower grade, and longer flotation time appeared to give somewhat higher nickel recoveries. Furthermore, the copper and nickel recoveries appeared to be consistently better than those obtained in a Fagergren cell. Hence, in the subsequent flotation tests the sample weight was fixed at 1200 grams, the percent solids in the rougher at 36 percent, and the flotation time in the rougher at 5 minutes, and in the cleaner at 3 minutes, unless stated otherwise.

2.4.2 Effect of Mesh-of-Grind

In a previous study at the Mineral Resources Research Center[6] on an Inco's Maturi shaft sample, designated IP9003 in the present investigation, a flowsheet involving a rougher flotation at a coarse grind to 100 mesh followed by regrinding of the rougher concentrates to 270 mesh and reflotation was developed. In a pilot plant study by the U.S. Bureau of Mines on an Inco's Spruce Road pit sample,[8] similar to IP9002 in the present investigation,

TABLE 9. EFFECTS OF PERCENT SOLIDS, SAMPLE WEIGHT AND FLOTATION TIME (MINUS 200 MESH GRIND, 0.05 LB PER TON KAX, 0.05 LB PER TON MIBC)

Test No.	Sample Wt, grams	Sample % Solids	Rougher Flot, Min	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec
1	1200	36	5	Cl Conc	6.32	6.20	1.46	92.89	63.44
				Cl Tail	15.20	0.09	0.09	3.32	9.66
				R Tail	78.48	0.02	0.05	3.79	26.90
2	1200	23	5	Cl Conc	5.17	7.10	1.67	91.29	66.66
				Cl Tail	5.08	0.15	0.13	1.99	5.43
				R Tail	89.75	0.03	0.04	6.72	27.91
3	1200	36	5	Cl 2 Conc	5.04	8.25	1.83	93.27	62.16
				Cl 2 Tail	1.79	0.24	0.02	0.90	2.70
				Cl 1 Tail	14.61	0.07	0.09	2.24	8.79
				R Tail	78.56	0.02	0.05	3.59	26.35
4	600	22	5	Cl 2 Conc	3.62	10.60	2.30	89.10	56.08
				Cl 2 Tail	1.87	0.57	0.58	2.55	7.43
				Cl 1 Tail	6.41	0.16	0.16	2.32	6.76
				R Tail	88.10	0.03	0.05	6.03	29.73
5	1200	36	10	Cl 2 Conc	4.22	9.24	2.18	89.87	65.71
				Cl 2 Tail	2.84	0.36	0.21	2.30	4.29
				Cl 1 Tail	13.56	0.07	0.07	2.30	7.14
				R Tail	79.38	0.03	0.04	5.53	22.86

the material was ground to minus 200 mesh prior to flotation. Metallurgically, in general, the finer the grind, the higher the grade and recovery, but the higher the energy requirements. Environmentally, however, finer grinding could perhaps lead to greater amounts of potentially hazardous fibrous mineral particles in the pulps. Conversely, coarser grinding results in more unliberated residual sulfides that could release heavy metal ions in tailing ponds upon oxidation. The mesh-of-grind, therefore, may be regarded as one of the more important parameters in the present investigation.

The recoveries of copper and nickel will be dependent not only on the mesh-of-grind, but also on the type and the amount of the collector and frother used. The flotation results at grinds of minus 48, 65, and 100 mesh, when both KAX and MIBC were held at 0.05 pound per ton, are given in Table 10. The effect of the mesh-of-grind is shown by the losses in copper and nickel to rougher tailings (R Tail). The results at minus 200 mesh are already given in Tests 1 and 4 in Table 9. It is apparent that both the copper and the nickel losses to the R Tails reach plateaus at 5 to 6 percent and about 25 percent, respectively. Lowering of the level of KAX addition to 0.025 pound per ton as well as the use of sodium isopropyl xanthate have little effect on the copper and nickel losses. It is also noted that the concentrates after two cleaning operations analyzed in excess of 10 percent copper in some tests, but apparently the mesh-of-grind did not govern the grades of concentrates directly.

It has been reported that the grinding media affected the flotation behavior of some sulfide ores. A few preliminary tests were performed by grinding the ore in a specially modified carbon steel ball mill. A 3/8-inch hole had been drilled through the bottom of the mill and another

TABLE 10. EFFECT OF MESH-OF-GRIND
(36 PERCENT SOLIDS, 0.05 LB PER TON MIBC)

Test No.	Grind, Min	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec
		Potassium Amyl Xanthate 0.05 lb per ton					
7	15 (-48 mesh)	Cl 2 Conc	4.35	7.57	1.69	79.65	56.45
		Cl 2 Tail	3.51	0.65	0.22	5.52	5.91
		Cl 1 Tail	7.31	0.20	0.09	3.53	5.07
		R Tail	84.83	0.055	0.05	11.30	32.57
12	20 (-65 mesh)	Cl 2 Conc	5.44	6.85	1.60	85.56	62.14
		Cl 2 Tail	4.39	0.42	0.16	4.23	5.00
		Cl 1 Tail	8.81	0.09	0.06	1.81	3.79
		R Tail	81.36	0.045	0.05	8.40	29.07
8	30 (-100 mesh)	Cl 2 Conc	6.76	5.63	1.25	90.97	67.00
		Cl 2 Tail	2.99	0.20	0.10	1.43	2.38
		Cl 1 Tail	11.80	0.07	0.06	1.98	5.63
		R Tail	78.45	0.03	0.04	5.62	24.92
		Potassium Amyl Xanthate 0.025 lb per ton					
20	30 (-100 mesh)	Cl 2 Conc	4.60	7.53	1.97	86.04	67.56
		Cl 2 Tail	3.68	0.55	0.21	5.02	5.74
		Cl 1 Tail	9.77	0.10	0.073	2.43	5.29
		R Tail	81.95	0.032	0.035	6.51	21.41
6	60 (-200 mesh)	Cl 2 Conc	3.86	10.02	2.21	88.97	57.82
		Cl 2 Tail	2.42	0.41	0.32	2.30	5.44
		Cl 1 Tail	11.63	0.11	0.11	2.98	8.84
		R Tail	82.09	0.03	0.05	5.75	27.89

(Continued)

TABLE 10 (Continued)

Test No.	Grind, Min	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec
		Sodium Isopropyl Xanthate 0.05 lb per ton					
10	15 (-48 mesh)	Cl 2 Conc	4.27	7.40	1.79	78.22	57.83
		Cl 2 Tail	2.93	0.63	0.25	4.58	5.53
		Cl 1 Tail	6.51	0.14	0.08	2.25	3.94
		R Tail	86.29	0.07	0.05	14.95	32.70
11	20 (-65 mesh)	Cl 2 Conc	5.27	6.90	1.69	84.97	66.34
		Cl 2 Tail	3.13	0.41	0.18	2.99	4.17
		Cl 1 Tail	7.49	0.125	0.08	2.20	4.47
		R Tail	84.11	0.05	0.04	9.84	25.02
21	30 (-100 mesh)	Cl 2 Conc	4.42	7.92	2.04	86.21	59.82
		Cl 2 Tail	3.58	0.54	0.28	4.75	6.63
		Cl 1 Tail	10.18	0.103	0.103	2.58	6.96
		R Tail	81.82	0.032	0.049	6.45	26.59
9	60 (-200 mesh)	Cl 2 Conc	6.94	5.55	1.38	92.91	70.18
		Cl 2 Tail	5.02	0.12	0.10	1.45	3.66
		Cl 1 Tail	19.46	0.05	0.06	2.34	8.57
		R Tail	68.58	0.02	0.035	3.30	17.59

through the lid of the mill to allow the passage of air through the mill during grinding in an attempt to simulate the continuous mill. The flotation results are presented in Table 11. In the table the flotation results after grinding in a carbon steel ball mill were virtually identical to those after grinding in a stainless steel rod mill. Hence, stainless steel rod mills were used in all the subsequent tests.

2.4.3 Level of Collector Addition

The amount of collector used in flotation should be minimized not only for economic reasons, but also for minimizing its residual concentration in tailing pulps. To investigate the effect of the level of KAX addition on metallurgical results and its residual concentrations in the tailing pulps, two series of flotation tests were performed, namely, on a sample ground to minus 200 mesh and on another ground to minus 100 mesh. The results together with relevant flotation conditions are given in Table 12.

The flotation results on minus 200-mesh samples remained virtually identical even when the KAX addition was increased from 0.01 to 0.1 pound per ton, whereas the residual concentration of KAX increased from 0.6 to 6.7 ppm. Similar observations may be made on minus 100-mesh samples although the copper and nickel recoveries were somewhat lower and the residual concentrations somewhat higher. Such an observation is in line with the difference in their surface areas in coarsening the grind from minus 200 mesh to minus 100 mesh. Assuming that the KAX used had a purity of 69 percent (see Section 2.3.3), the amount of abstraction in each test may be estimated as shown in Table 13.

TABLE 11. EFFECT OF GRINDING IN AN AIR-CIRCULATED CARBON STEEL BALL MILL (36 PERCENT SOLIDS, 0.05 LB PER TON KAX, 0.05 LB PER TON MIBC)

Test No.	Grind, Min	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec
13	30 (-100 mesh)	Cl 2 Conc	6.27	6.90	1.52	90.10	65.00
		Cl 2 Tail	3.57	0.29	0.13	2.17	3.14
		Cl 1 Tail	15.86	0.07	0.06	2.31	6.48
		R Tail	74.30	0.035	0.05	5.42	25.38
14	60 (-200 mesh)	Cl 2 Conc	4.59	8.19	1.81	91.50	61.06
		Cl 2 Tail	4.06	0.20	0.14	1.97	4.19
		Cl 1 Tail	15.99	0.05	0.06	1.95	7.05
		R Tail	75.36	0.025	0.05	4.58	27.70

TABLE 12. EFFECT OF LEVEL OF KAX ADDITION
(36 PERCENT SOLIDS, 0.05 LB PER TON MIBC)

Test No.	KAX lb/ton	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	esidual KAX ppm
			Minus 200 Mesh Grind					
16	0.01	Cl 2 Conc	5.12	7.01	1.78	90.04	57.55	
		Cl 2 Tail	5.01	0.24	0.155	3.01	4.93	
		Cl 1 Tail	16.30	0.075	0.089	3.06	9.16	
		R Tail	73.57	0.021	0.061	3.89	28.36	0.6
15	0.05	Cl 2 Conc	4.90	7.97	1.82	91.69	59.35	
		Cl 2 Tail	2.23	0.28	0.18	1.46	2.66	
		Cl 1 Tail	13.33	0.07	0.10	2.18	8.85	
		R Tail	79.54	0.025	0.055	4.67	29.14	2.4
17	0.1	Cl 2 Conc	5.84	6.23	1.69	90.75	64.34	
		Cl 2 Tail	3.58	0.22	0.121	1.97	2.80	
		Cl 1 Tail	16.73	0.064	0.063	2.67	6.85	
		R Tail	73.85	0.025	0.054	4.61	26.01	6.7
			Minus 100 Mesh Grind					
18	0.01	Cl 2 Conc	5.38	6.83	1.86	84.07	56.87	
		Cl 2 Tail	3,51	0.58	0.19	4.67	3.81	
		Cl 1 Tail	10.48	0.115	0.083	2.77	4.94	
		R Tail	80.63	0.046	0.075	8.49	34.38	0.9
19	0.1	Cl 2 Conc	6.35	5.19	1.53	85.05	59.74	
		Cl 2 Tail	4.08	0.45	0.16	4.75	4.00	
		Cl 1 Tail	10.96	0.13	0.10	11.10	6.76	
		R Tail	78.61	0.032	0.061	6.50	29.50	8.4

TABLE 13. ABSTRACTION OF KAX IN FLOTATION

Grind	KAX lb/ton	Residual KAX, ppm	% Abstracted
-200 mesh	0.01	0.6	77
	0.05	2.4	81
	0.1	6.7	74
-100 mesh	0.01	0.9	65
	0.1	8.4	68

It is readily apparent that 65 to 80 percent of the KAX added to the flotation pulps was abstracted and much of the collector removed with the sulfide concentrates. The residual concentrations of the xanthate in flotation tailings would be on the order of 1 to 2 ppm.

2.4.4 Level of Frother Addition

The amount of a frother in flotation is critical since its use in insufficient quantities adversely affects the flotation recovery whereas its use in excess results often in low-grade concentrates due to contamination by gangue particles trapped and carried over into the froth. The effect of the level of MIBC addition was investigated on samples ground to minus 100 mesh as before. The MIBC concentrations in pulp solutions were analyzed at four points: before and after roughing and before the first and second cleaner operations. Since MIBC molecules are adsorbed at the air-water interface, frothing during flotation tends to accumulate this surfactant into the concentrate pulps. The flotation results together with the residual concentrations of KAX and MIBC are given in Table 14.

The effect of the amount of the frother addition is clearly reflected in the weight recovery and the concentrate grade, namely the higher the frother addition, the higher the weight recovery and also the lower the

TABLE 14. EFFECT OF LEVEL OF MIBC ADDITION
(MINUS 100 MESH GRIND, 36 PERCENT SOLIDS, 0.05 LB PER TON KAX)

Test No.	MIBC lb/ton	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec	Residual Conc, ppm KAX	Residual Conc, ppm MIBC
23	0.025	Cl 2 Conc	2.22	14.20	2.44	73.68	39.73	2.22	14.20	2.44	73.68	39.73		
		Cl 2 Tail	1.21	1.43	1.37	4.04	12.17	3.43	9.69	2.06	77.72	51.90		
		Cl 1 Tail	7.35	0.52	0.31	8.93	16.72	10.78	3.44	0.87	86.65	68.62	0.5	0.73[d]
													2.5	3.8[c]
		R Tail	89.22	0.064	0.048	13.35	31.38	100.00	0.43	0.14	100.00	100.00	0.8	2.8[b]
													8.7	7.1[a]
22	0.05	Cl 2 Conc	3.37	10.00	2.34	73.92	54.95	3.37	10.00	2.34	73.92	54.95		
		Cl 2 Tail	4.28	0.75	0.33	7.04	9.82	7.65	4.82	1.22	80.96	64.77		
		Cl 1 Tail	9.49	0.19	0.105	3.95	6.96	17.14	2.26	0.60	84.91	71.73	0.6	3.3
													1.1	8.6
		R Tail	82.86	0.083	0.049	15.09	28.27	100.00	0.46	0.14	100.00	100.00	1.2	5.6
													6.9	17.0
24	0.075	Cl 2 Conc	4.66	7.91	2.10	80.09	62.49	4.66	7.91	2.10	80.09	62.49		
		Cl 2 Tail	5.65	0.46	0.17	5.65	6.08	10.31	3.83	1.05	85.74	68.57		
		Cl 1 Tail	10.49	0.24	0.088	5.48	5.83	20.80	2.02	0.56	91.22	74.40	0.5	7.6
													1.2	17.0
		R Tail	79.20	0.051	0.051	8.78	25.60	100.00	0.46	0.16	100.00	100.00	1.1	7.8
													9.7	30.2

[a]Before Rougher flotation
[b]After Rougher flotation
[c]Before Cleaner 1 flotation
[d]Before Cleaner 2 flotation

concentrate grade. The optimum appeared to be at 0.05 pound per ton. The solution concentration of MIBC before roughing may be used to estimate the amount of abstraction as before. Table 15 summarizes the results assuming that the MIBC used was a pure compound. (The same MIBC was used to establish the calibration line. See Section 2.4.)

TABLE 15. ABSTRACTION OF MIBC IN CONDITIONING PRIOR TO ROUGHER FLOTATION (MINUS 100 MESH GRIND, 0.05 LB PER TON KAX)

Test No.	MIBC lb/ton	Residual MIBC, ppm	% Abstracted
23	0.025	7.1	24
22	0.05	17.0	9
24	0.075	30.2	(-7)

The analytical results are seen to scatter into positive as well as negative directions. Such an observation might be taken to mean that the amount of the frother abstracted by the solid sample was relatively small. The variation of the MIBC concentration within a test is in line with an interpretation that much of the frother was carried over in the froth into the concentrate fraction. The correlation of the observed flotation behavior with the analytical results of residual MIBC concentrations indicates that the optimum level of the frother would be in the neighborhood of 10 ppm in flotation pulp solutions.

2.4.5 Repeated Cleaning of Concentrates

Since the grades of concentrates after two cleaner operations seldom exceeded 10 percent copper regardless of the mesh-of-grind and the levels of the collector and frother additions, the cleaner flotation operation

was extended to four stages to see if the concentrate grade could be further improved. Initially the effect of the mesh-of-grind was investigated at constant KAX and MIBC additions of 0.05 pound per ton. In the cleaner flotation stages the frother had to be supplemented as needed, usually 0.025 pound per ton in the third stage. The flotation results thus obtained are given in Table 16.

In the table it is seen that three to four stages of cleaner flotation were needed to improve the grade of copper to 12 percent and that the recoveries of copper and nickel improved somewhat by finer grinding. The latter point is well illustrated in the grade-recovery plot (Figure 17). In Tests 29 and 30 the effect of reducing the level of frother addition is shown. It is interesting to note that the concentrate grade could be improved to over 14 percent copper and over 3 percent nickel without appreciably sacrificing their recoveries by maintaining a proper level of the frother.

2.4.6 Regrinding and Reflotation of Concentrates (Two-stage Grind Flotation)

It had been established earlier that the coarsest mesh-of-grind without appreciable loss of copper and nickel was minus 65 mesh. Since the amount of sulfide minerals was relatively small, it became of interest to recover a concentrate at a coarse grind and regrind the concentrate for further cleaning, thereby alleviating the grinding cost, as well as perhaps reducing the amount of fibrous mineral particles generated, and also further improving the concentrate grade. The sample was ground either to minus 48, 65 or 100 mesh and the rougher and cleaner flotation steps were carried out as before, followed by regrinding of the cleaner concentrate to minus 270 mesh and

TABLE 16. EFFECT OF 4-STAGE CLEANER FLOTATION
(36 PERCENT SOLIDS, 0.05 LB PER TON KAX)

Test No.	Grind Min	MIBC lb/ton	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
26	20 (-65 mesh)	0.05	Cl 4 Conc	2.40	14.37	3.41	77.35	52.14	2.40	14.37	3.41	77.35	52.14
			Cl 4 Tail	0.65	2.48	1.46	3.61	6.06	3.05	11.84	2.99	80.96	58.20
			Cl 3 Tail	0.92	1.42	0.61	2.94	3.57	3.97	9.42	2.44	83.90	61.77
			Cl 2 Tail	4.00	0.84	0.29	7.54	7.39	7.97	5.12	1.36	91.44	69.16
			Cl 1 Tail	7.87	0.10	0.08	1.77	4.02	15.84	2.62	0.73	93.21	73.18
			R Tail	84.16	0.036	0.05	6.79	26.82	100.00	0.45	0.16	100.00	100.00
27	30 (-100 mesh)	0.05	Cl 4 Conc	2.73	12.99	2.84	80.92	58.35	2.73	12.99	2.84	80.92	58.35
			Cl 4 Tail	0.21	1.98	0.85	0.96	1.36	2.94	12.20	2.70	81.88	59.71
			Cl 3 Tail	0.61	1.40	0.63	1.94	2.86	3.55	10.35	2.34	83.82	62.57
			Cl 2 Tail	4.01	0.77	0.25	7.05	7.53	7.56	5.27	1.23	90.87	70.10
			Cl 1 Tail	9.06	0.11	0.07	2.28	4.74	16.62	2.46	0.60	93.15	74.84
			R Tail	83.38	0.036	0.04	6.85	25.16	100.00	0.44	0.13	100.00	100.00
28	60 (-200 mesh)	0.05	Cl 4 Conc	3.31	11.63	2.61	87.50	63.77	3.31	11.63	2.61	87.50	63.77
			Cl 4 Tail	0.30	1.27	0.55	0.86	1.26	3.61	10.77	2.44	88.36	65.03
			Cl 3 Tail	0.48	0.79	0.39	0.86	1.40	4.09	9.60	2.21	89.22	66.43
			Cl 2 Tail	2.77	0.41	0.19	2.59	3.91	6.86	5.89	1.39	91.81	70.34
			Cl 1 Tail	14.61	0.08	0.06	2.66	6.49	21.47	1.94	0.49	94.47	76.83
			R Tail	78.53	0.031	0.04	5.53	23.17	100.00	0.44	0.14	100.00	100.00
29	30 (-100 mesh)	0.016	Cl 4 Conc	2.38	15.17	3.24	79.29	52.45	2.38	15.17	3.24	79.29	52.45
			Cl 4 Tail	0.24	2.30	1.57	1.21	2.59	2.62	13.99	3.09	80.50	55.04
			Cl 3 Tail	0.42	1.92	1.13	1.78	3.27	3.04	12.33	2.82	82.28	58.31
			Cl 2 Tail	1.13	1.26	0.72	3.12	5.51	4.17	9.33	2.25	85.40	63.82
			Cl 1 Tail	5.29	0.40	0.15	4.66	5.37	9.46	4.34	1.08	90.06	69.19
			R Tail	90.54	0.05	0.05	9.94	30.81	100.00	0.46	0.15	100.00	100.00

(Continued)

TABLE 16 (Continued)

Test No.	Grind Min	MIBC lb/ton	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
30	30 (-100 mesh)	0.024	Cl 4 Conc	2.39	14.97	3.25	82.46	56.92	2.39	14.97	3.25	82.46	56.92
			Cl 4 Tail	0.22	2.30	1.34	1.18	2.20	2.61	13.90	3.09	83.64	59.12
			Cl 3 Tail	0.41	1.79	0.89	1.71	2.71	3.02	12.26	2.80	85.35	61.83
			Cl 2 Tail	1.42	1.05	0.56	3.43	5.86	4.44	8.68	2.08	88.78	67.69
			Cl 1 Tail	8.37	0.31	0.11	5.99	6.74	12.81	3.21	0.79	94.77	74.43
			R Tail	87.19	0.026	0.04	5.23	25.57	100.00	0.43	0.14	100.00	100.00

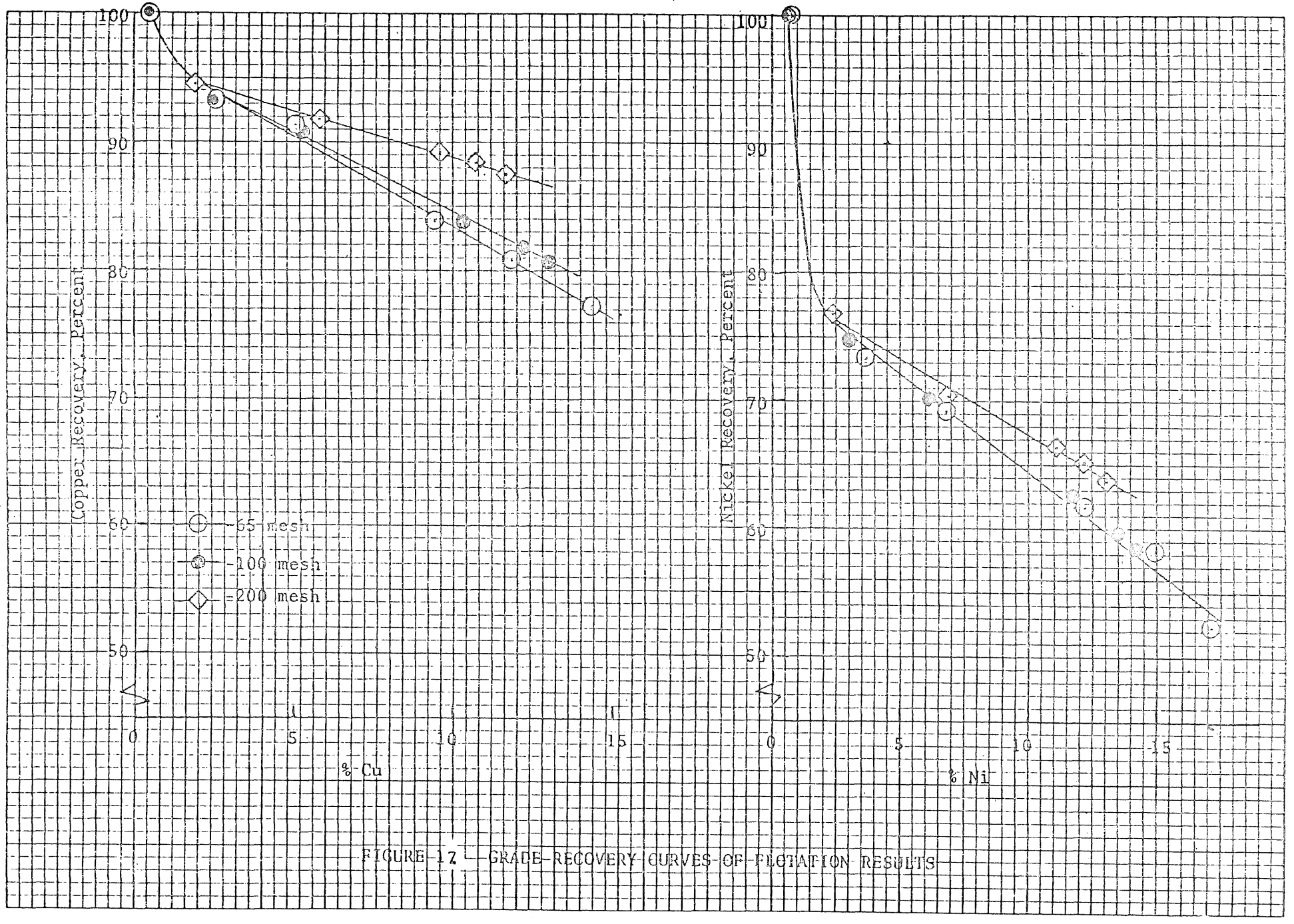


FIGURE 17 — GRADE-RECOVERY CURVES OF FLOTATION RESULTS

reflotation. No additional KAX was added in the reflotation stage, but the frother was applied as needed. The results are given in Table 17.

In the table it is seen that the concentrate grades were improved to 16 percent copper and over 3 percent nickel, and that there were virtually no differences in metallurgical results between minus 65- and minus 100-mesh grinds, but at minus 48 mesh the copper recoveries were appreciably lower, in agreement with the results in Table 10. It appears, therefore, that the present type of flowsheet should be compared with a simple flowsheet consisting of grinding and repeated flotation operations with regard to their energy consumption and fibrous particle generation potential. The effect of the mesh-of-grind in the regrinding step was not fully investigated and this particular point warrants more detailed optimization study as well as mineralogical investigation on middling particles.

2.4.7 Flotation Time and Froth Removal Rate

The nickel contents of rougher tailings were seen to center around 0.05 percent with occasional variations to 0.04 or 0.06 percent. Since pentlandite and pyrrhotite are known to be slow-floating minerals,[7] it was thought desirable to check the effect of flotation time. In fact, it was noted during Test 5 that a longer flotation time (10 minutes) appeared to give a somewhat higher nickel recovery (Table 9). In addition, it was felt during the course of investigation that the grade of concentrates might be improved by slower rates of froth removal.

To check these two points a few additional tests were made on samples ground to minus 200 mesh. These tests were also used to find out if any problems might be encountered in the sampling procedures just developed.

TABLE 17. ROUGHER-CLEANER FLOTATION AT COARSE GRIND FOLLOWED BY REGRINDING OF CLEANER CONCENTRATE TO MINUS 270 MESH AND RECLEANER FLOTATION (36 PERCENT SOLIDS, 0.05 LB PER TON KAX, 0.05 LB PER TON MIBC)

Test No.	Primary Grind Min	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
25	30	Regr Cl Conc	3.38	10.49	2.21	84.73	49.67	3.38	10.49	2.21	84.73	49.67
	(-100 mesh)	Regr Cl Tail	5.13	0.30	0.45	3.58	15.23	8.51	4.35	1.15	88.31	64.90
		Cl Tail	9.19	0.13	0.10	2.86	5.96	17.70	2.16	0.60	91.17	70.86
		R Tail	82.30	0.045	0.053	8.83	29.14	100.00	0.42	0.15	100.00	100.00
33	15	Regr Cl 4 Conc	1.86	17.65	3.31	74.85	45.10	1.86	17.65	3.31	74.85	45.10
	(-48 mesh)	Regr Cl 4 Tail	0.13	1.98	2.95	0.59	2.78	1.99	16.63	3.29	75.44	47.88
		Regr Cl 3 Tail	0.25	1.65	1.37	0.94	2.49	2.24	14.96	3.07	76.38	50.37
		Regr Cl 2 Tail	0.94	0.67	0.72	1.44	4.98	3.18	10.73	2.38	77.82	55.35
		Regr Cl 1 Tail	4.26	0.31	0.23	3.01	7.17	7.44	4.77	1.15	80.83	62.52
		Cl Tail	6.77	0.24	0.10	3.72	4.83	14.20	2.91	0.65	84.55	67.35
		R Tail	85.79	0.079	0.052	15.45	32.65	100.00	0.44	0.14	100.00	100.00
31	20	Regr Cl 4 Conc	2.16	16.50	3.33	86.14	44.37	2.16	16.50	3.33	86.14	44.37
	(-65 mesh)	Regr Cl 4 Tail	0.11	1.63	2.28	0.44	1.54	2.27	15.78	3.28	86.58	45.91
		Regr Cl 3 Tail	0.48	0.74	1.29	0.87	3.83	2.75	13.16	2.93	87.45	49.74
		Regr Cl 2 Tail	1.26	0.32	0.48	0.97	3.77	4.01	9.12	2.16	88.42	53.51
		Regr Cl 1 Tail	4.09	0.10	0.19	0.99	4.82	8.10	4.57	1.17	89.41	58.33
		Cl Tail	7.83	0.13	0.11	2.47	5.31	15.93	2.39	0.65	91.88	63.64
		R Tail	84.07	0.04	0.07	8.12	36.36	100.00	0.41	0.16	100.00	100.00
32	30	Regr Cl 4 Conc	2.27	16.10	3.39	82.65	48.07	2.27	16.10	3.39	82.65	48.07
	(-100 mesh)	Regr Cl 4 Tail	0.15	1.33	2.10	0.45	2.00	2.42	15.19	3.31	83.10	50.07
		Regr Cl 3 Tail	0.42	0.68	1.11	0.66	2.93	2.84	13.04	2.99	83.76	53.00
		Regr Cl 2 Tail	1.26	0.41	0.70	1.18	5.49	4.10	9.16	2.29	84.94	58.49
		Regr Cl 1 Tail	4.84	0.14	0.16	1.54	4.81	8.94	4.28	1.13	86.48	63.30
		Cl Tail	10.39	0.11	0.10	2.58	6.49	19.33	2.04	0.58	89.06	69.79
		R Tail	80.67	0.06	0.06	10.94	30.21	100.00	0.44	0.16	100.00	100.00

In Test 34 the levels of KAX and MIBC additions and the durations of the conditioning times were kept the same as before, but the rougher flotation time was extended to 10 minutes and the cleaner flotation time to 5 minutes. The froth was removed at a slower rate than before in an attempt to minimize the amount of gangue pulled into the froth. The results are given in Table 18. It is noted that the weight percent of the rougher tailing was considerably higher than before and that the grade of concentrate even after two stages of cleaner flotation was in excess of 13 percent copper, but the recoveries of copper and nickel suffered somewhat. Hence in Test 35 an attempt was made to improve the loading characteristics of the froths by increasing the amount of the frother addition to 0.075 pound per ton. The flotation results, however, remained essentially the same. These observations suggest that the manner in which the froth is removed is important, particularly when a material with appreciable quantities of unliberated particles is being dealt with. In the standardized flotation tests on different Duluth gabbro samples the levels of both the collector and the frother additions were fixed at 0.05 pound per ton, and the rougher flotation time was fixed at 10 minutes and the cleaner flotation time at 5 minutes with a standardized rate of froth removal to allow comparison of the flotation results.

The solution concentrations of KAX and MIBC before and after the rougher flotation are also included in the table. The abstraction of KAX is estimated to be about 90 percent, which is in good agreement with the data presented in Table 13. The solution concentrations of MIBC were greater than those calculated by assuming that the frother was not abstracted. It would appear that very little frother was adsorbed on solid particles.

TABLE 18. EFFECT OF LONGER FLOTATION TIME
(MINUS 200 MESH GRIND, 36 PERCENT SOLIDS, 0.05 LB PER TON KAX, ROUGHER 10 MINUTES, CLEANER 5 MINUTES)

Test No.	MIBC lb/ton	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec	Residual Conc, ppm KAX	Residual Conc, ppm MIBC
34	0.05	Cl 3 Conc	2.43	16.21	2.04	87.30	30.73	2.43	16.21	2.04	87.30	31.90		
		Cl 3 Tail	0.83	1.12	2.93	2.06	15.06	3.26	12.37	2.27	89.36	42.19		
		Cl 2 Tail	2.18	0.48	0.89	2.33	12.02	5.44	7.60	1.72	91.69	54.21		
		Cl 1 Tail	8.72	0.155	0.19	2.99	10.29	14.16	3.02	0.78	94.68	69.27		
		R Tail	85.84	0.028	0.06	5.32	31.90	100.00	0.45	0.16	100.00	100.00	1.5	13.2[b]
													5.5	23.2[a]
35	0.075	Cl 3 Conc	2.13	18.23	1.50	82.41	20.45	2.13	18.23	1.50	82.41	20.45		
		Cl 3 Tail	0.96	1.44	3.60	2.93	22.11	3.09	13.01	2.16	85.34	42.56		
		Cl 2 Tail	2.49	0.51	1.19	2.70	18.91	5.58	7.43	1.72	88.04	61.47		
		Cl 1 Tail	8.80	0.135	0.15	2.52	8.43	14.38	2.97	0.76	90.56	69.90		
		R Tail	85.62	0.052	0.055	9.44	30.10	100.00	0.47	0.16	100.00	100.00	1.1	23.8
													2.5	32.8

[a]Before Rougher flotation
[b]After Rougher flotation

This is also in agreement with the observations made on the results presented in Table 15.

2.4.8 Dilution Factors for Flotation Products in Fiber Count Analyses

Samples for fiber count analyses were prepared by dispersing a feed, rougher tailing (R Tail), or fourth cleaner concentrate (Cl 4 Conc) pulp in an Andreasen pipette and withdrawing 10 milliliters at certain time intervals in a similar manner to that used in the determination of size distribution. Dispersants were not used, however, to approximate the real situations. In fact, feed and rougher tailing samples were noted to be dispersed in distilled water. Although cleaner concentrates were not dispersed in equivolume mixtures of water and alcohol, it was felt that fibrous silicate minerals would be dispersed as in feed and rougher tailing samples, and, both silicate and sulfide minerals being negatively charged, these minerals would not mutually flocculate. In order to arrive at the dilution factors between pulp samples and Andreasen pipette samples that were filtered on Nuclepore filters for fibrous mineral characterization under an electron microscope, first the solid and water contents of flotation feed and its products had to be known.

In batch flotation tests a considerable amount of make-up water was added to maintain the pulp level for froth removal, which would reduce the fiber content by dilution. To estimate the fiber contents of concentrate and tailing pulps in batch flotation tests it was assumed that:

(1) there was no preferential accumulation of fiber particles in the froths or cell products (i.e., fiber particles behave like water),

(2) the suspension was perfectly mixed,

(3) make-up water was added at constant rates though in steps. With t[illegible] assumptions it may be shown that the removal of fiber particles follows the first-order rate and the concentration of fiber particles decreases exponentially according to

$$\frac{C}{Co} = e^{\frac{-t}{\theta}} \qquad \ldots . \quad (8)$$

where

Co: concentration of fiber particles in feed

C: concentration of fiber particles in cell product

t: flotation time

θ: mean retention time = $\frac{\text{average volume of water in flotation cell}}{\text{rate of make-up water addition}}$

Table 19 shows typical examples of solid and water weight data of flotation products both in the one-stage grind flotation and in the two-stage grind flotation tests. Also included in the table are the relative fiber concentrations (C/Co) calculated by applying Equation 8 to the water weight data.

The dilution factors for timed samples in an Andreasen pipette were estimated in the following manner. First, a pulp sample was diluted in an Andreasen pipette to the 20-cm mark. The volume to this mark of the Andreasen pipette used in the present investigation was 528 milliliters. The dilution factor here should allow for the presence of solids in pulp samples. After timed samples of 10 milliliters had been withdrawn, the pipette (P in Figure 9) was washed with exactly 25 milliliters of distilled water, allowing the use of a fixed dilution factor here of 3.5.

TABLE 19. EFFECT OF DILUTION OF FLOTATION PRODUCTS ON FIBER COUNT ANALYSES

	Weight, grams		Relative Fiber Concentration
	Solids	Water	
(a) One-stage Grind Flotation			
Rougher Feed	1200	1800	1.00
Tail	890	2240	0.33
Conc	256	1780	0.59
Cleaner 1 Feed	256	2380	0.44
Tail	168	1860	0.34
Conc	88	1060	0.39
Cleaner 2 Feed	88	2260	0.18
Tail	28	1800	0.13
Conc	60	1100	0.16
Cleaner 3 Feed	60	2000	0.088
Tail	21	2000	0.060
Conc	39	750	0.073
Cleaner 4 Feed	39	2050	0.027
Tail	6	1900	0.020
Conc	33	700	0.024
(b) Two-stage Grind Flotation			
Rougher Feed	1200	1800	1.00
Tail	990	1900	0.36
Conc	210	1800	0.62
Cleaner Feed	210	2000	0.56
Tail	103	2000	0.31
Conc	107	1200	0.42
Regrind Feed*	321	3000	0.42**
Regr Cl 1 Feed	321	2100	0.42**
Tail	176	1800	0.42**
Conc	145	1120	0.42**
Regr Cl 2 Feed	145	1870	0.25
Tail	32	2100	0.12
Conc	113	1180	0.18
Regr Cl 3 Feed	113	2080	0.10
Tail	9	2100	0.048
Conc	104	1570	0.072
Regr Cl 4 Feed	104	2070	0.055
Tail	5.5	2200	0.028
Conc	98.5	1300	0.040

* Three Cleaner Concs combined

** Excess supernatant water of combined Cleaner Concs used in Regrinding and Regr Cl 1 flotation steps

The dilution factors for individual pulp samples and the overall dilution factors including the dilution water used in flotation were estimated as shown below.

One-stage Grind Flotation

Feed: Fifteen milliliters of a pulp at 36 percent solids was diluted to 528 milliliters in an Andreasen pipette. Since the pulp sample consisted of 12.6 milliliters of water and 7.1 grams (or 2.4 milliliters) of solids, the dilution factor would be

$$\frac{528 - 2.4}{12.6} \times 3.5 = 146 \quad \ldots . \quad (9)$$

R Tail: Twenty milliliters of a pulp with 28 percent solids was used in this example. The pulp sample consisted of 17.7 milliliters of water and 7.0 grams (or 2.3 milliliters) of solids. The dilution factor would be

$$\frac{528 - 2.3}{17.7} \times 3.5 = 104 \quad \ldots . \quad (10)$$

and the overall dilution factor would be

$$\frac{104}{0.33} = 315 \quad \ldots . \quad (11)$$

Cl 4 Conc: To the fourth cleaner concentrate (Cl 4 Conc) pulp sufficient amounts of denatured alcohol and distilled water were added to have equal volume mixture of these two solvents and a total volume of two liters in a 2-liter Denver cell. For the fiber count analysis 400 milliliters of the suspensions in an equal volume mixture of alcohol and water (hence a factor of 2 in Equation 11) was used. Neglecting the percent solids corrections the dilution factor would be

$$2 \times \frac{528}{400} \times 3.5 \times \frac{2000}{700} = 26.4 \quad \ldots . \quad (12)$$

and the overall dilution factor would be

$$\frac{26.4}{0.024} = 1100 \quad \ldots . \quad (13)$$

Two-stage Grind Flotation

Feed: Same as that in 'One-stage Grind Flotation.'

R Tail: Twenty milliliters of a pulp at 34 percent solids, consisting of 17 milliliters of water and 8.9 grams (or 3.0 milliliters) of solids, was used. Hence, the dilution factor would be

$$\frac{528 - 3.0}{17.0} \times 3.5 = 108 \quad \ldots . \quad (14)$$

and the overall dilution factor would be

$$\frac{108}{0.36} = 300 \quad \ldots . \quad (15)$$

Regr Cl 4 Conc: The pulp at 7.0 percent solids was diluted with an equal volume of denatured alcohol and 100 milliliters of the suspension was used. Hence, neglecting the percent solid correction the dilution factor would be

$$2 \times \frac{528}{100} \times 3.5 = 37 \quad \ldots . \quad (16)$$

and the overall dilution factor would be

$$\frac{37}{0.040} = 924 \quad \ldots . \quad (17)$$

In the foregoing calculations the dilution factors for feeds remained identical and could be rounded off to 150. The dilution factors for rougher tailings remained about the same and could be estimated to be 105, and the overall dilution factor 300. The dilution factors and the overall dilution factors for fourth cleaner concentrates (Cl 4 Conc) in one-stage grind flotation and two-stage grind flotation are seen to center around 30 and 1000, respectively, although their sampling procedures were quite different. Errors involved in the dilution factor for Feed are expected to be quite small, say less than a few percent, since all the parameters are well defined.

Errors for R Tail would still be relatively small, say on the order of 5 to 10 percent, since the amounts of solids and water removed in rougher flotation depended on the sample. Errors for Cl 4 Conc would be quite large, perhaps as high as 25 to 50 percent, since the pulp volume of froth products varied appreciably from sample to sample. The dilution factors and the overall dilution factors that will be used in the present investigation are summarized in Table 20.

TABLE 20. DILUTION FACTORS FOR FLOTATION PRODUCTS IN FIBER COUNT ANALYSES

	Dilution Factors	Overall Dilution Factors
Feed	150	150
R Tail	105	300
Cl 4 Conc	30	1000

Theoretically, the fiber count data, reported by Mr. Kyle Bishop, multiplied by the overall dilution factors should, therefore, be about the same corresponding to the fiber count of feed pulp.

2.5 STANDARDIZED TEST PROCEDURES

2.5.1 Flotation Procedures

2.5.1.1 One-stage Grind Flotation Tests

(1) Twelve hundred grams of a minus 10-mesh sample and 1200 milliliters of distilled water were placed in a stainless steel rod mill and ground to nominal minus 200 mesh.

(2) The ground pulp was transferred to a Denver cell, diluted to volume (two liters) with distilled water.

(3) To the agitated pulp 0.05 pound of KAX per ton was added, conditioned for two minutes, then 0.05 pound of MIBC per ton added, conditioned for one minute, the pulp pH and temperature measured, and the froth removed in a standardized manner for 10 minutes.

(4) The froth product was returned to a Denver cell, diluted to volume with distilled water and floated for 5 minutes. The cleaner flotation was repeated three more times using additional frother as needed.

(5) Two identical flotation tests were carried out and the respective flotation products were combined. All the products were filtered, placed in pans, dried in an oven held at 105°C, weighed, assayed for copper, nickel, cobalt, iron and sulfur, and the metallurgical balance calculated. The fourth cleaner concentrate (Cl 4 Conc) was analyzed also for graphite carbon.

(6) An additional flotation test was carried out, and the pulp samples of R Tail and Cl 4 Conc were used for obtaining fiber, size distribution and water chemistry analysis samples.

(7) Three additional flotation tests were carried out for preparing the environmental leaching samples. The remaining fourth cleaner concentrate (C1 4 Conc) in Item (5) was added to these concentrates.

2.5.1.2 Two-stage Grind Flotation Tests

(1) Twelve hundred grams of a minus 10-mesh sample and 1200 milliliters of distilled water were placed in a stainless steel rod mill and ground to nominal minus 65 mesh.

(2) The ground pulp was transferred to a Denver cell, diluted to volume with distilled water.

(3) To the agitated pulp 0.05 pound of KAX per ton was added, conditioned for two minutes, then 0.05 pound of MIBC per ton added, conditioned for one minute, the pulp pH and temperature measured, and floated for 10 minutes.

(4) The froth product was returned to a Denver cell, diluted to volume with distilled water and floated for 5 minutes.

(5) Two additional flotation tests were carried out and the three cleaner concentrates were combined, ground in a stainless steel rod mill at 50 percent solids to nominal minus 270 mesh.

(6) The ground pulp was transferred to a Denver cell, diluted to volume with distilled water and floated for 5 minutes. The cleaner flotation was repeated three more times using additional frother as needed.

(7) All the products were filtered, placed in pans, dried in an oven held at 105°C, weighed, and the metallurgical balance calculated.

(8) The concentrate and tailing samples after assaying were used in the environmental leaching.

(9) An identical flotation test starting with three 1200-gram samples was carried out for obtaining the fiber, size distribution, and water chemistry analysis samples. The fourth cleaner concentrate (Cl 4 Conc) and the rougher tailing (R Tail) samples were assayed for copper, nickel, cobalt, iron and sulfur.

2.5.2 Pulp Sampling Procedures

2.5.2.1 Flotation Feed

(1) Six samples, approximately 15 milliliters of pulp each, were siphoned out half way down the pulp level in a 2-liter Denver cell while agitating with the air off, and were used in the following tests.

i. Determination of size distribution by the Andreasen pipette method.

ii. Fiber count analysis of a minus 37-μm fraction obtained with an Andreasen pipette. The dilution factor for this sample was 150.

iii. Size fractionation to +20, 20/10, 10/5 and -5 μm by the sedimentation sizing method, and trace element analysis of the sized products dried by evaporation.

(2) A 250-milliliter pulp (150 gram solid, dry basis) sample was siphoned out and dried by evaporation for chemical analyses of major elements and for trace element analysis.

(3) A 75-milliliter pulp (50 gram solid, dry basis) sample was siphoned out and wet screened into +100, 100/150, 150/200, 200/270, 270/400 and -400 mesh fractions for mineralogical study.

(4) Supernatant water was centrifuged to remove solids and used in trace element analysis.

2.5.2.2 Rougher Flotation Tailing

(1) Six samples, approximately 20 milliliters of pulp each, were siphoned out about half way down the pulp level in a Denver cell as before after rougher flotation, and were used in the following tests.

i. Determination of size distribution by the Andreasen pipette method.

ii. Fiber count analyses of seven samples at -37, -20, -10 and -5 μm, 4 hours, 24 hours and 48 hours obtained with an Andreasen pipette. The dilution factor for these samples was 300.

iii. Fiber count analysis of -37 μm fraction obtained by decanting 90 percent of the supernatant water after 48 hours in the above test, adding fresh distilled water to volume and resuspending the particles. This -37 μm fraction was to compare the amount of fine particles of colloidal size. The dilution factor for this sample was 3000.

iv. Size fractionation to +20, 20/10, 10/5 and -5 μm by the sedimentation sizing method, and trace element analysis of the sized products dried by evaporation.

(2) A 300-milliliter pulp (150 gram solid, dry basis) sample was siphoned out and dried by evaporation for chemical analyses of major elements and for trace element analysis.

(3) A 100-milliliter pulp (50 gram solid, dry basis) sample was siphoned out, wet screened into +100, 100/150, 150/200, 200/270, 270/400 and -400 mesh fractions for mineralogcial study.

(4) Chemical analyses of water sample obtained by centrifuging as follows:

3.1 FLOTATION TESTS ON IP9002 SAMPLE

Sample Description

An Inco pit sample, weighing 3 tons, was received on March 31, 1974. The sample, which had been designated Ore No. 1881 at the Mineral Resources Research Center, was relabeled IP9002 in the present investigation. It was a part of a 10,000-ton sample removed in 1974 from a test pit on the Spruce Road about 4 miles east of Minnesota State Highway 1 near the South Kawishiwi River. The same sample was used previously in a study of differential flotation.[7] A 120-ton sample from the same location was used by the U. S. Bureau of Mines in a continuous pilot-plant flotation investigation for recovering bulk sulfide concentrates.[8]

The sample was crushed through one inch in a jaw crusher and split into four portions. One portion was further crushed to minus 1/4 inch in a laboratory jaw crusher and then to minus 10 mesh through a rolls crusher. The minus 10-mesh sample was split into 1200-gram lots. The head analysis of the sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF IP9002 SAMPLE

Constituent	Percent
Copper (Cu)	0.45
Nickel (Ni)	0.15
Cobalt (Co)	0.017
Iron (Fe)	9.43
Sulfur (S)	0.98
Titanium dioxide (TiO_2)	(1.0)*
Graphite carbon (C)	0.047

*From reference 8

Grinding Characteristics

The grinding characteristics of the IP9002 sample were investigated by grinding 1200-gram batches of minus 10-mesh feed in a stainless steel laboratory rod mill at 50 percent solids for various periods of time. The size distributions of the minus 10-mesh feed and of a sample ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. These results have been transposed directly from Chapter 2 - Development of Test Procedures. The size distribution data of the ground batches are seen to be represented by straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.92. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF ORE 1955 (IP9002) IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50 PERCENT SOLIDS)

Nominal Mesh-of-Grind	Grind Time Minutes	Size Modulus k, µm	80% passing µm
-10 mesh	0	-	1220
-48 mesh	15	300	240
-65 mesh	20	235	180
-100 mesh	30	140	110
-200 mesh	60	88	70

pH
xanthate
MIBC
trace elements

(5) Determination of the effect of aging on water chemical analyses. A rougher tailing pulp was transferred to a 2-liter beaker with a minimum of dilution and water samples obtained after 1 day, 1 week, and 1 month for pH, xanthate, MIBC and trace element analyses.

2.5.2.3 Cleaner Concentrate

(1) A concentrate sample was diluted with denatured alcohol and distilled water in a Denver cell so that the solvent consisted of an equal volume mixture of alcohol and water and the total pulp volume was 2000 milliliters. While agitating with the air off, four 400-milliliter pulp samples were split out for the following determinations.

i. Determination of size distribution by the Andreasen pipette method.

ii. Fiber count analysis of a minus 37-μm fraction obtained with an Andreasen pipette. The dilution factor in both one-stage grind flotation and two-stage grind flotation tests was 1000.

iii. Size fractionation to +20, 20/10, 10/5, and -5 μm by the sedimentation sizing method, and trace element analysis of the sized products dried by evaporation.

(2) A combined concentrate sample from two identical tests was split into two portions and used in the following tests.

i. Mineralogical study after wet screening into +100, 100/150, 150/200, 200/270, 270/400, and -400 mesh fractions and drying.

ii. Chemical analyses for major elements and trace element analysis.

3.0 FLOTATION TEST RESULTS OF INDIVIDUAL SAMPLES

In this chapter the results of bench-scale flotation tests on eleven different Duluth gabbro samples are presented. The essence of the findings will be summarized in Chapter 4.

TABLE 2. SCREEN ANALYSIS OF IP9002 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 mesh		15 min		20 min		30 min		60 min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
10	0.2	100.0	-	-	-	-	-	-	-	-
14	23.6	99.8	-	-	-	-	-	-	-	-
20	13.2	76.2	-	-	-	-	-	-	-	-
28	14.2	63.0	-	-	-	-	-	-	-	-
35	10.2	48.8	0.8	100.0	-	-	-	-	-	-
48	9.2	38.6	8.1	99.2	2.0	100.0	-	-	-	-
65	5.9	29.4	17.4	91.1	10.0	98.0	-	-	-	-
100	6.6	23.5	19.8	73.7	20.0	88.0	5.4	100.0	-	-
150	6.6	16.9	16.6	53.9	19.5	68.0	16.6	94.6	4.0	100.0
200	3.4	10.3	12.6	37.3	13.5	48.5	21.0	78.0	11.5	96.0
270	1.8	6.9	4.4	24.7	9.0	35.0	15.2	57.0	22.8	84.5
325	1.0	5.1	3.0	20.3	5.0	26.0	6.8	41.8	10.5	61.7
400	0.6	4.1	2.4	17.3	2.4	21.0	5.0	35.0	7.4	51.2
500	1.3	3.5	2.8	14.9	4.1	18.6	5.4	30.0	8.5	43.8
-500	2.2	2.2	12.1	12.1	14.5	14.5	24.6	24.6	35.3	35.3

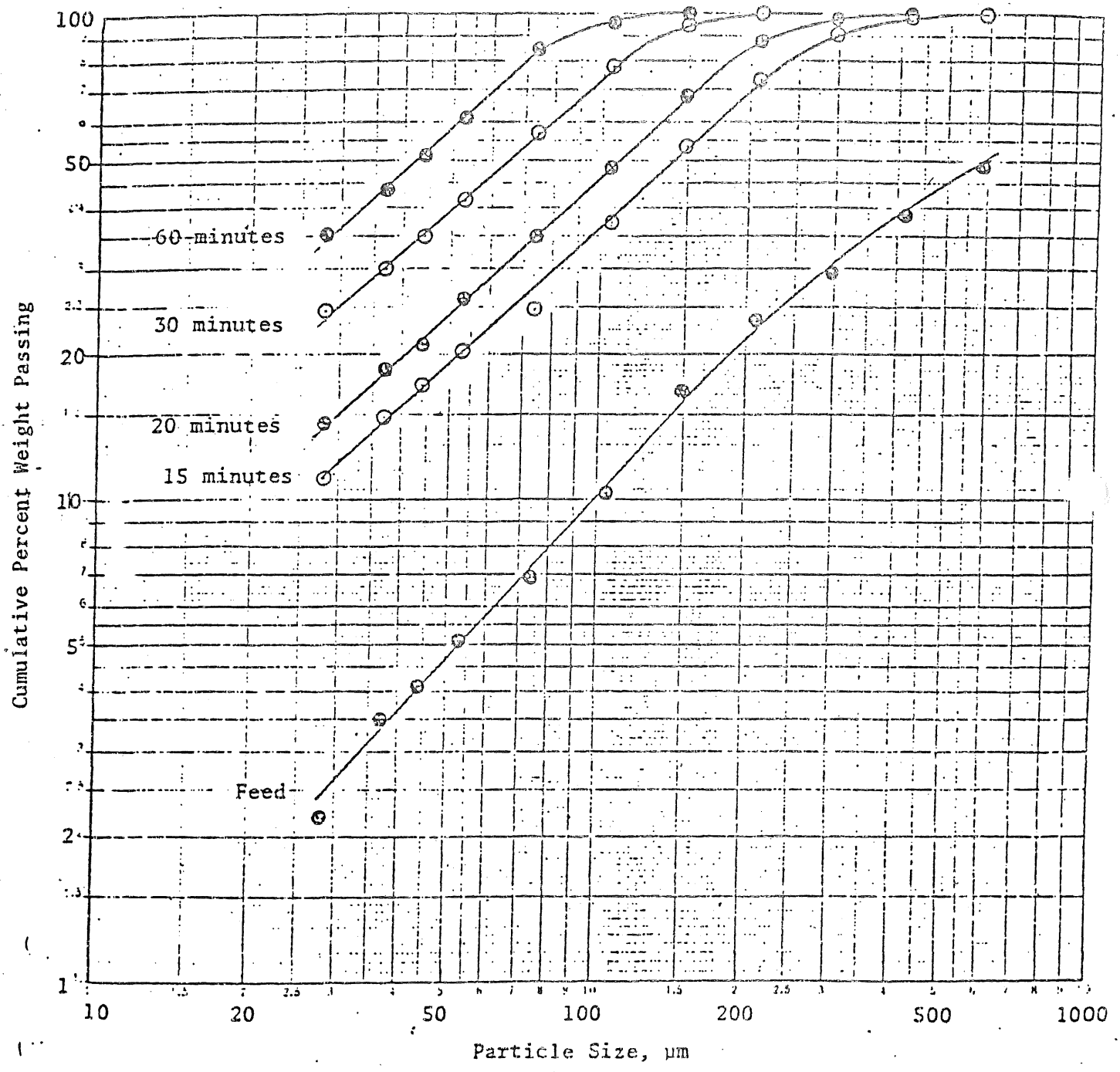


FIGURE 1. SIZE DISTRIBUTIONS OF IP9002 SAMPLE AS A FUNCTION OF GRINDING TIME

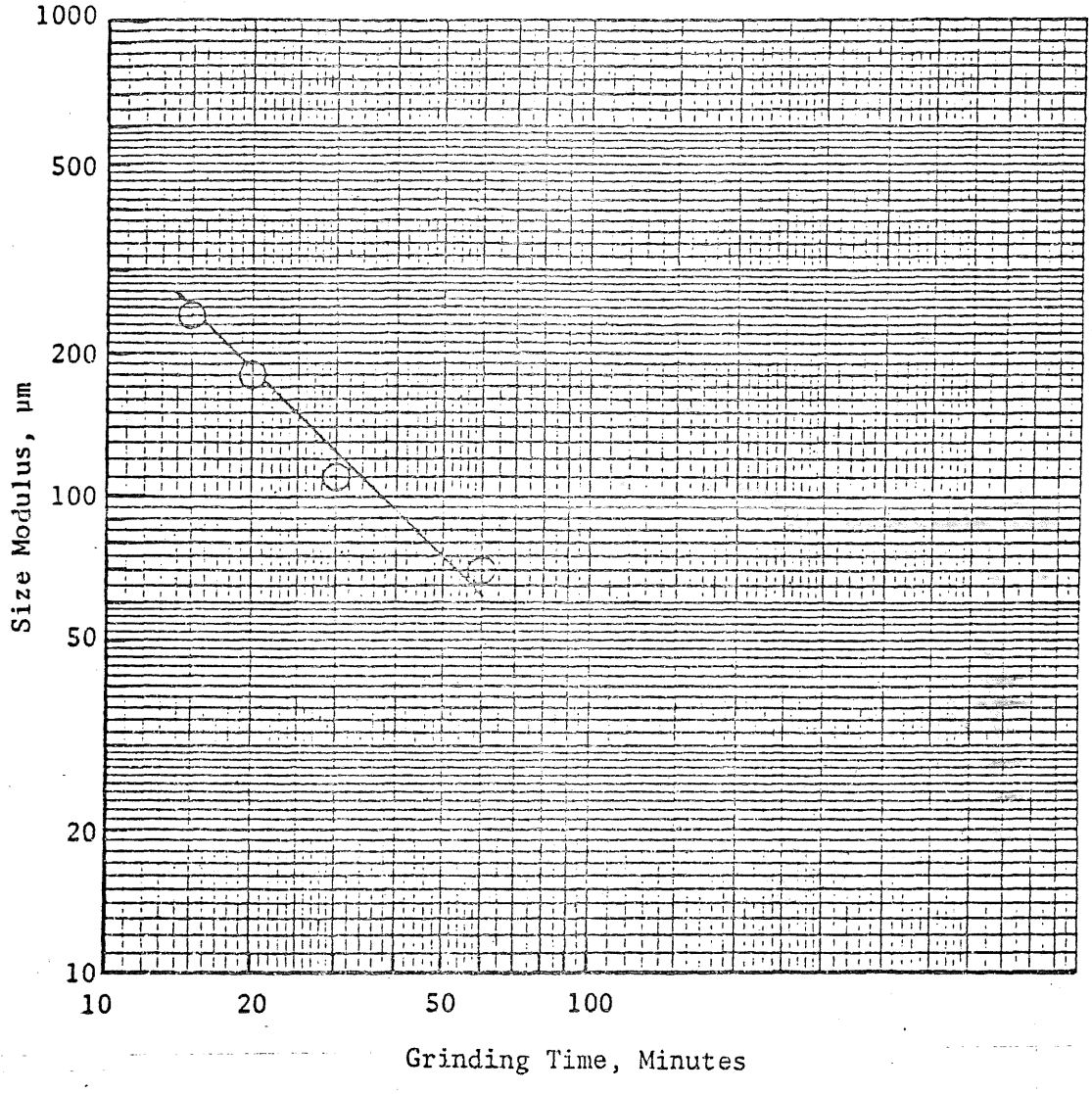


FIGURE 2. SIZE MODULI OF IP9002 SAMPLE AS A FUNCTION OF GRINDING TIME

Preliminary Flotation Tests

The effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh, and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed at 3 minutes. The results of these flotation tests are given in Table 4.

It is apparent in Table 4 that both the losses of copper and of nickel to the R Tails reached plateaus at about 5 percent and 25 percent, respectively, for minus 100- and 200-mesh grind samples. The losses of copper and nickel to R Tails tended to increase somewhat at 65 mesh and noticeably at 48 mesh. It is also noted that the concentrates after three cleaner stages analyzed in excess of 12 percent copper and approached 2.5 percent nickel. These observations are quite similar to the flotation behaviors of AMAX shaft composite sample (AX9002).

Since the standardized flotation and pulp sampling procedures were developed on this sample, the details of the preliminary flotation results can be seen in Chapter 2.

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground

TABLE 4. EFFECT OF MESH-OF-GRIND ON IP9002
Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Flotation Time: Rougher 5 min, Cleaner 3 min

Test No.	Grind, Min	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
7	15 (-48 mesh)	Cl 2 Conc	4.35	7.57	1.69	79.65	56.45	4.35	7.57	1.69	79.65	56.45
		Cl 2 Tail	3.51	0.65	0.22	5.52	5.91	7.86	4.48	1.03	85.17	62.36
		Cl 1 Tail	7.31	0.20	0.09	3.53	5.07	15.17	2.42	0.58	88.70	67.43
		R Tail	84.83	0.055	0.05	11.30	32.57	100.00	0.41	0.13	100.00	100.00
12	20 (-65 mesh)	Cl 2 Conc	5.44	6.85	1.60	85.56	62.14	5.44	6.85	1.60	85.56	62.14
		Cl 2 Tail	4.39	0.42	0.16	4.23	5.00	9.83	3.98	0.96	89.79	67.14
		Cl 1 Tail	8.81	0.09	0.06	1.81	3.79	18.64	2.14	0.53	91.60	70.93
		R Tail	81.36	0.045	0.05	8.40	29.07	100.00	0.44	0.14	100.00	100.00
8	30 (-100 mesh)	Cl 2 Conc	6.76	5.63	1.25	90.97	67.07	6.76	5.63	1.25	90.97	67.07
		Cl 2 Tail	2.99	0.20	0.10	1.43	2.38	9.75	3.97	0.90	92.40	69.45
		Cl 1 Tail	11.80	0.07	0.06	1.98	5.63	21.55	1.83	0.44	94.38	75.08
		R Tail	78.45	0.03	0.04	5.62	24.92	100.00	0.42	0.13	100.00	100.00
3	60 (-200 mesh)	Cl 2 Conc	5.04	8.25	1.83	93.27	62.16	5.04	8.25	1.83	93.27	62.16
		Cl 2 Tail	1.79	0.24	0.02	0.90	2.70	6.83	6.15	1.41	94.17	64.86
		Cl 1 Tail	14.61	0.07	0.09	2.24	8.79	21.44	2.01	0.51	96.41	73.65
		R Tail	78.56	0.02	0.05	3.59	26.35	100.00	0.45	0.15	100.00	100.00
26	20 (-65 mesh)	Cl 4 Conc	2.40	14.37	3.41	77.35	52.14	2.40	14.37	3.41	77.35	52.14
		Cl 4 Tail	0.65	2.48	1.46	3.61	6.06	3.05	11.84	2.99	80.96	58.20
		Cl 3 Tail	0.92	1.42	0.61	2.94	3.57	3.97	9.42	2.44	83.90	61.77
		Cl 2 Tail	4.00	0.84	0.29	7.54	7.39	7.97	5.12	1.36	91.44	69.16
		Cl 1 Tail	7.87	0.10	0.08	1.77	4.02	15.84	2.62	0.73	93.21	73.18
		R Tail	84.16	0.036	0.05	6.79	26.82	100.00	0.45	0.16	100.00	100.00

(Continued)

TABLE 4 (CONTINUED)

Test No.	Grind, Min	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
27	30 (-100 mesh)	Cl 4 Conc	2.73	12.99	2.84	80.92	58.35	2.73	12.99	2.84	80.92	58.35
		Cl 4 Tail	0.21	1.98	0.85	0.96	1.36	2.94	12.20	2.70	81.88	59.71
		Cl 3 Tail	0.61	1.40	0.63	1.94	2.86	3.55	10.35	2.34	83.82	62.57
		Cl 2 Tail	4.01	0.77	0.25	7.05	7.53	7.56	5.27	1.23	90.87	70.10
		Cl 1 Tail	9.06	0.11	0.07	2.28	4.74	16.62	2.46	0.60	93.15	74.84
		R Tail	83.38	0.036	0.04	6.85	25.16	100.00	0.44	0.13	100.00	100.00
28	60 (-200 mesh)	Cl 4 Conc	3.31	11.63	2.61	87.50	63.77	3.31	11.63	2.61	87.50	63.77
		Cl 4 Tail	0.30	1.27	0.55	0.86	1.26	3.61	10.77	2.44	88.36	65.03
		Cl 3 Tail	0.48	0.79	0.39	0.86	1.40	4.09	9.60	2.21	89.22	66.43
		Cl 2 Tail	2.77	0.41	0.19	2.59	3.91	6.86	5.89	1.39	91.81	70.34
		Cl 1 Tail	14.61	0.08	0.06	2.66	6.49	21.47	1.94	0.49	94.47	76.83
		R Tail	78.53	0.031	0.04	5.53	23.17	100.00	0.44	0.14	100.00	100.00

cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 92.64%, 65.70%, and 90.76%, respectively, at 200 mesh (one-stage grind flotation), and were 92.13%, 73.27%, and 91.12%, respectively, at 65 mesh (two-stage grind flotation). The flotation concentrate could be upgraded to 15.50 percent copper and 2.39 percent nickel in the one-stage grind flotation after three cleanings, whereas in the two-stage grind flotation the concentrate was upgraded to 14.84 percent copper and 3.01 percent nickel after two cleanings following regrinding. The sum of the copper, nickel, cobalt, iron, and sulfur contents may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The third cleaner concentrate (Cl 3 Conc) in the one-stage grind flotation would then have 33.7 percent gangue and the reground second cleaner concentrate (Regr Cl 2 Conc) in the two-stage grind flotation would have 30.3 percent gangue.

A Davis magnetic tube test was performed on a Cl 4 Conc sample to explore the feasibility of a copper-nickel separation, but the magnetic concentrate amounted to only 1.59 percent by weight. Hence, chemical analyses on the magnetic separation products were not made. Evidently, the pyrrhotite in the present sample is the nonmagnetic variety.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, and R Tail samples in the one-stage grind flotation test and the Feed, Regr Cl 4 Conc, Cl Tail, and R Tail samples in the two-stage grind flotation test were analyzed by Barringer Research Ltd. The

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON IP9002

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 40 Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 34°C Rougher pH: 9.3							
Cl 4 Conc	2.55	16.71	2.56	0.09	27.92	22.48	0.43
Cl 4 Tail	0.21	0.87	0.34	0.033	15.98	5.21	-
Cl 3 Tail	0.54	0.33	0.17	0.025	12.35	1.74	-
Cl 2 Tail	2.21	0.26	0.11	0.02	12.82	2.95	-
Cl 1 Tail	14.04	0.074	0.055	0.02	9.00	0.35	-
R Tail	80.45	0.044	0.05	0.02	8.01	0.09	-
Flotation Feed	100.00	0.48	0.14	0.02	9.20	0.99	0.047
Test No. 41 Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 35°C Rougher pH: 9.2							
Regr Cl 4 Conc	2.48	16.60	3.20	0.166	29.52	25.53	0.48
Regr Cl 4 Tail	0.13	1.42	2.10	0.11	20.62	9.17	-
Regr Cl 3 Tail	0.19	1.06	1.17	0.068	16.50	6.13	-
Regr Cl 2 Tail	0.64	0.60	0.55	0.039	14.01	4.45	-
Regr Cl 1 Tail	2.95	0.31	0.20	0.021	12.48	3.19	-
Cl Tail	8.86	0.199	0.096	0.020	10.00	1.02	-
R Tail	84.75	0.045	0.044	0.013	8.32	0.10	-
Flotation Feed	100.00	0.53	0.11	0.018	9.03	0.86	-

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON IP9002

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 40 One-stage Grind Flotation																	
Cleaner 4	2.55	16.71	2.56	0.09	27.92	22.48	88.53	55.71	10.55	8.09	73.56	97.45	0.057	0.053	0.020	8.30	0.211
Cleaner 3	2.76	15.50	2.39	0.09	27.03	21.16	88.90	56.31	11.01	8.48	74.97	97.24	0.055	0.053	0.020	8.29	0.201
Cleaner 2	3.30	13.02	2.03	0.08	24.64	17.97	89.27	57.08	11.47	9.24	76.13	96.70	0.053	0.052	0.020	8.26	0.192
Cleaner 1	5.51	7.90	1.26	0.05	19.89	11.94	90.48	59.13	13.31	12.45	84.47	94.49	0.049	0.051	0.020	8.15	0.128
Rougher	19.55	2.28	0.40	0.03	12.07	3.61	92.64	65.70	26.15	26.81	90.76	80.45	0.044	0.050	0.020	8.01	0.090
Test No. 41 Two-stage Grind Flotation																	
Regr Cleaner 4	2.48	16.60	3.20	0.166	29.52	25.53	85.01	56.92	22.76	7.94	66.33	97.52	0.075	0.062	0.014	8.68	0.330
Regr Cleaner 3	2.61	15.85	3.15	0.161	29.12	24.71	85.40	58.86	23.34	8.27	67.58	97.39	0.073	0.059	0.014	8.66	0.318
Regr Cleaner 2	2.80	14.84	3.01	0.154	28.21	23.45	85.81	60.44	23.90	8.60	68.81	97.20	0.071	0.057	0.014	8.64	0.306
Regr Cleaner 1	3.44	12.19	2.55	0.134	25.58	19.92	86.60	62.95	25.57	9.58	71.80	96.56	0.067	0.053	0.014	8.61	0.279
Cleaner	6.39	6.71	1.47	0.081	19.56	12.20	88.50	67.18	28.90	13.61	81.60	93.61	0.060	0.049	0.014	8.48	0.187
Rougher	15.25	2.93	0.67	0.046	14.03	5.70	92.13	73.27	38.90	23.29	91.12	84.75	0.045	0.044	0.013	8.32	0.100

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF IP9002

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 40 - One-stage Grind Flotation (Minus 200 mesh)		
+150	1.33	2.09	2.35
+200	5.34	3.72	10.59
+270	25.25	13.02	24.58
+400	15.91	16.05	17.91
-400	52.17	65.12	44.57
	(b) Test 41 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	5.61	-	0.25
+65	11.83	-	3.39
+100	21.94	-	19.61
+150	13.05	-	23.10
+200	16.33	-	25.11
+270	7.21	2.45	8.55
+400	4.34	13.43	5.40
-400	14.69	84.12	14.59

*Cl 4 Conc and Regr Cl 4 Conc, respectively

results are given in Table 7 and 8. In these tables it is seen that approximately 0.01 percent arsenic was present in the present sample and virtually all of it reported in the flotation tailings. It is also noted that the concentration of such trace elements as zinc and silver notably increased. The amounts of cadmium, lead and mercury in the cleaner concentrates increased to some extent. These increases are apparently due to the close association of these elements with sulfide minerals. The analyses of phosphorus in the concentrate samples were unexpectedly high. Hence a wet chemical analysis was performed on a one-stage grind flotation concentrate. It showed that the phosphorus value reported by Barringer might be in error. Hence, a duplicate analysis was requested and the duplicate results showed the phosphurs to be 'not detectable.' Whereas the zinc, cobalt and nickel analyses by Barringer and by the MRRC are in reasonably good agreement, the copper and iron analyses of the one-stage grind flotation concentrate (Table 7) differ appreciably. It is surprising that these values were closely duplicated by Barringer. The silicon analyses in Tables 7 and 8 appear to be unreasonably low since the feed and tailing samples were essentially silicates.

Mineralogical studies were made on this sample in connection with the differential flotation studies sponsored by the U. S. Bureau of Mines.[5] The liberation characteristics of sulfide minerals appear to be quite similar to those of AX9002.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred

TABLE 7. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON IP9002 (TEST 40 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Cl 4 Conc (-200 mesh)			R Tail (-200 mesh)	
	Barringer	MRRC*	Barringer	Duplicate	MRRC*	Barringer	MRRC*
Al	10.90		3.55	3.19		11.50	
B	0.107		0.0214	0.0603		0.177	
Be	nd		nd	nd		nd	
Ca	6.48		2.40	2.16		6.84	
Cu	0.404	0.45	7.90	7.78	16.71	0.0122	0.044
Fe	8.65	9.43	19.20	18.1	27.92	7.60	8.01
Mg	4.75		4.70	2.73		4.55	
Mn	0.103		0.066	0.0645		0.0987	
P	0.201		1.23	nd	0.008**	0.121	
Ba	0.0716		0.015	0.0055		0.108	
Se	nd		nd	nd		nd	
Te	nd		nd	nd		nd	
As	0.012		0.006	nd		0.012	
Si	1.02		0.245	0.0511		1.63	
Sr	0.0349		0.0104	0.00763		0.0358	
Zr	0.0039		0.0019	0.00208		0.0047	
Ti	0.531		0.105	0.1		0.532	
V	0.0136		0.0140	0.00977		0.0132	
Zn	0.0154		0.0936	0.0997	0.062	0.0106	
Th	0.0011		0.0012	0.00113		0.0012	
K	0.18		0.17	0.095		0.22	
Na	2.54		0.737	0.62		2.79	
Cd	nd		0.0020	0.0035		nd	
Cr	0.0399		0.0123	0.017	0.012	0.0313	
Co	0.0114	0.017	0.1250	0.13	0.09	0.007	0.02
Ag	0.00054		0.00346	0.00278		0.00034	
Mo	nd		0.0032	0.0051		nd	
Ni	0.11	0.15	2.75	2.8	2.56	0.0273	0.05
Pb	nd		0.0070	0.013		nd	
Hg***	0.0000090		0.0000190			0.0000070	

(Continued)

TABLE 7 - CONTINUED (IP9002)

	Feed (-200 mesh)		Cl 4 Conc (-200 mesh)			R Tail (-200 mesh)	
	Barringer	MRRC*	Barringer	Duplicate	MRRC*	Barringer	MRRC*
F^-	22.9****						
Cl^-	293						
NO_2^-	30						
$PO_4^{\equiv}$	<40						
Br^-	<16						
NO_3^-	16						
$SO_4^{\equiv}$	457						

* Conventional AA analyses
** Wet chemical analysis
*** 0.0000001% = 1 ppb
****All the anion analysis results in ppm

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PROUDCTS ON IP9002 (TEST 41 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Regr Cl 4 Conc (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	11.00		1.13		10.60		11.10	
B	0.00044		0.00005		0.114		0.111	
Be	nd		nd		nd		nd	
Ca	6.64		0.769		6.40		6.64	
Cu	0.422	0.45	16.70	16.60	0.203	0.199	0.0297	0.045
Fe	8.02	9.43	30.20	29.52	9.34	10.00	8.21	8.32
Mg	4.74		2.50		4.95		4.80	
Mn	0.107		0.0315		0.106		0.105	
P	0.176		2.67		0.167		0.128	
Ba	0.0136		0.0026		0.0759		0.0742	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
As	0.011		0.002		0.012		0.010	
Si	0.0469		0.0412		1.09		1.06	
Sr	0.035		0.00317		0.0321		0.0343	
Zr	0.0021		0.0011		0.0045		0.0040	
Ti	0.4570		0.0361		0.514		0.583	
V	0.0129		0.0119		0.0153		0.0134	
Zn	0.0129		0.179		0.0156		0.0111	
Th	0.0011		0.0009		0.0012		0.0012	
K	0.16		0.18		0.20		0.15	
Na	2.42		0.244		2.35		2.54	
Cd	nd		0.003		nd		nd	
Cr	0.02		0.0108		0.0469		0.019	
Co	0.0102	0.017	0.147	0.166	0.01	0.020	0.0075	0.013
Ag	0.00052		0.00446		0.00056		0.00035	
Mo	nd		0.0008		0.0002		nd	
Ni	0.099	0.15	3.21	3.20	0.0847	0.096	0.0302	0.044
Pb	nd		0.013		nd		nd	

* Conventional AA analyses

to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were analyzed in a similar manner after one week and one month of standing. The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 9 shows the amounts of residual flotation reagents in the liquors. Tables 10 and 11 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease from near 9 during flotation to about 8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed appreciably in one week, and these reagents became virtually absent after one month. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors upon aging. Of particular interest is the fact that the concentration of copper remained near 10 ppb throughout the period. In fact, these values were lower than those in the distilled water used at that time. The decrease in the presence of the ore sample may be interpreted to be due to adsorption and that upon the addition of flotation reagents to the precipitation of insoluble copper xanthate. The concentrations of nickel ions in the pulp solutions remained essentially below the limit of detection by the analytical method used (90 ppb). Of note is the zinc ion concentration which eventually increased to a few tenths of one ppm in a month. Perhaps the zinc ions might have been released by the exchange reaction with copper and nickel ions.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of Table 6.

TABLE 9. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTION OF IP9002

Sampling Time	One-stage Grind Flotation (Test 40)			Two-stage Grind Flotation (Test 41)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	8.8	1.20	3.00	8.7	1.62	2.91
After 1 Day	8.3	0.46	1.53	8.3	1.04	1.58
After 1 Week	8.1	0.39	0.15	8.05	0.185	0.00
After 1 Month	8.2	0.24	0.00	8.0	0.183	0.00

TABLE 10. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF IP9002 (TEST 40 - MINUS 200 MESH GRIND)

	Distilled Water (6-7-77)	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al	nd	0.47	0.65	0.50	0.33	0.20
B	nd	0.052	0.040	0.050	0.031	0.047
Ba	nd	nd	nd	nd	nd	nd
Be	nd	nd	nd	nd	nd	nd
Ca	nd	10.3	17.0	13.8	13.5	19.2
Cu	0.127	nd	0.0035	nd	0.0126	0.012
Fe	nd	0.015	0.141	0.031	0.016	0.044
K	nd	10	12	9	9.2	1
Mg	nd	2.59	5.56	3.89	3.19	4.59
Mn	nd	0.0035	0.0158	0.0070	nd	nd
Na	nd	29.2	21.5	16.4	15.3	18
P	nd	0.4	0.4	nd	nd	nd
Se	nd	nd	nd	nd	nd	nd
Te	nd	nd	nd	nd	nd	nd
Pb	nd	nd	nd	nd	nd	0.2
Si	nd	5.19	4.99	4.60	4.44	4.53
Sr	nd	0.0228	0.0386	0.0327	0.0291	0.0371
Ti	nd	nd	nd	nd	0.0008	nd
V	nd	nd	nd	nd	0.002	nd
Zn	0.145	0.059	0.010	nd	nd	0.12
Th	nd	nd	nd	nd	nd	nd
Ag	nd	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	nd
Cd	nd	nd	nd	nd	nd	nd
Co	nd	nd	nd	nd	nd	nd
Cr	nd	0.013	0.012	0.008	nd	0.007
Mo	nd	nd	nd	nd	0.67	0.99
Ni	nd	nd	0.07	nd	nd	nd
Zr	nd	nd	nd	nd	nd	nd

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF IP9002 (TEST 41 - MINUS 65 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		0.75	0.66	0.50	0.22	0.33
B		0.032	0.030	0.026	0.034	0.018
Ba		nd	nd	nd	nd	nd
Be		nd	nd	nd	nd	nd
Ca		10.4	9.89	10.3	18.4	18.9
Cu		0.0075	0.0032	0.0032	0.011	0.012
Fe		0.176	0.071	0.042	0.025	0.149
K		6.4	10.1	6.6	1	11.3
Mg		3.06	4.30	3.42	4.91	4.31
Mn		0.0024	0.0024	0.0034	nd	0.0106
Na		13.9	11.3	8.7	13	12
P		nd	nd	nd	nd	nd
Se		nd	nd	nd	nd	nd
Te		nd	nd	nd	nd	nd
Pb		nd	nd	nd	nd	nd
Si		2.61	3.84	2.81	3.79	3.69
Sr		0.0248	0.0242	0.0230	0.034	0.0332
Ti		0.0024	0.0021	0.0021	nd	0.002
V		nd	0.002	nd	0.002	0.004
Zn		0.058	0.125	0.075	0.21	nd
Th		nd	nd	nd	nd	nd
Ag		nd	nd	nd	nd	nd
As		nd	nd	nd	0.2	nd
Cd		nd	nd	nd	nd	nd
Co		nd	nd	nd	nd	nd
Cr		0.007	0.006	0.009	0.017	0.015
Mo		0.64	0.50	0.42	0.84	0.61
Ni		nd	0.04	nd	nd	nd
Zr		nd	nd	nd	nd	nd

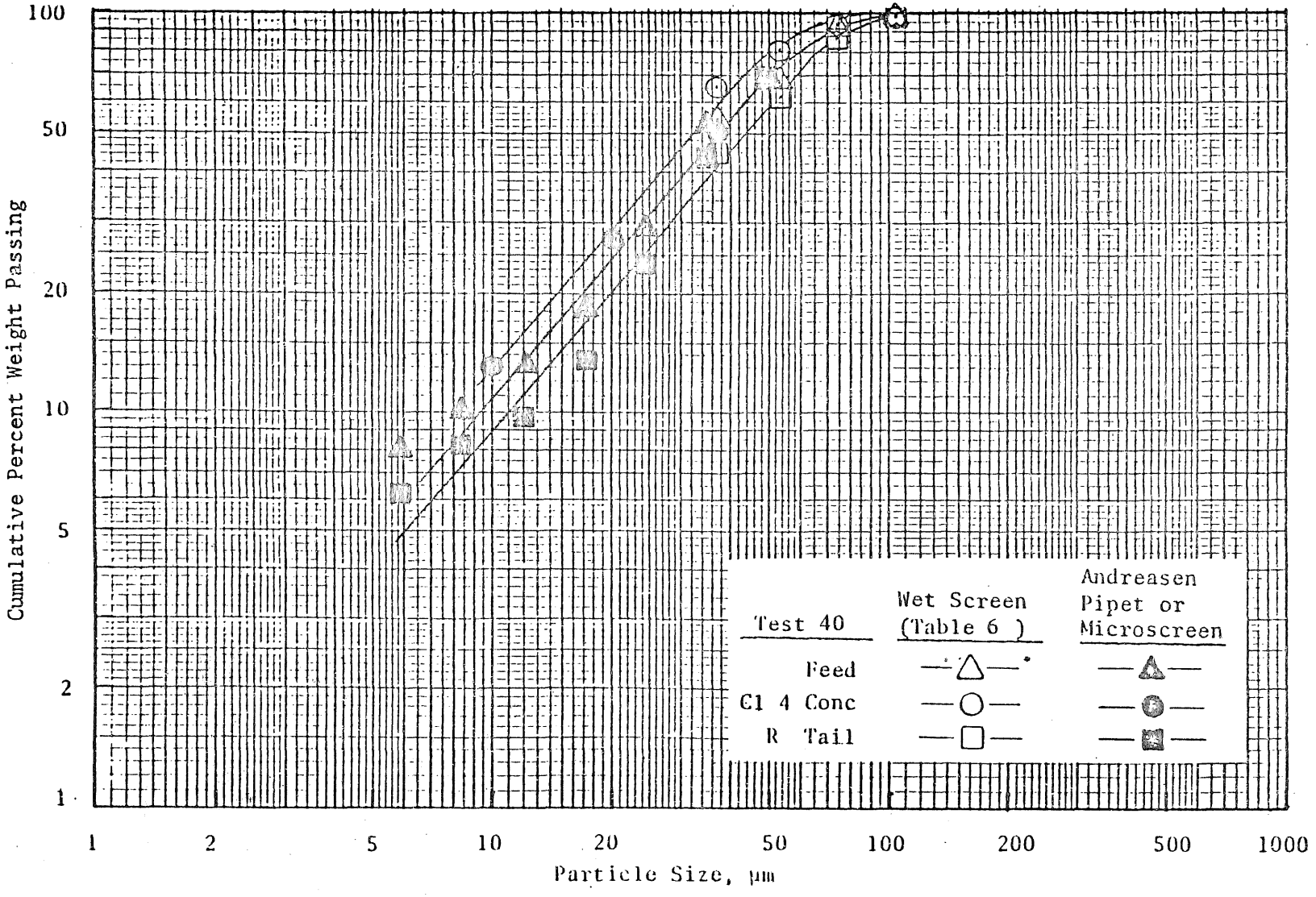


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF IP9002 (MINUS 200 MESH GRIND)

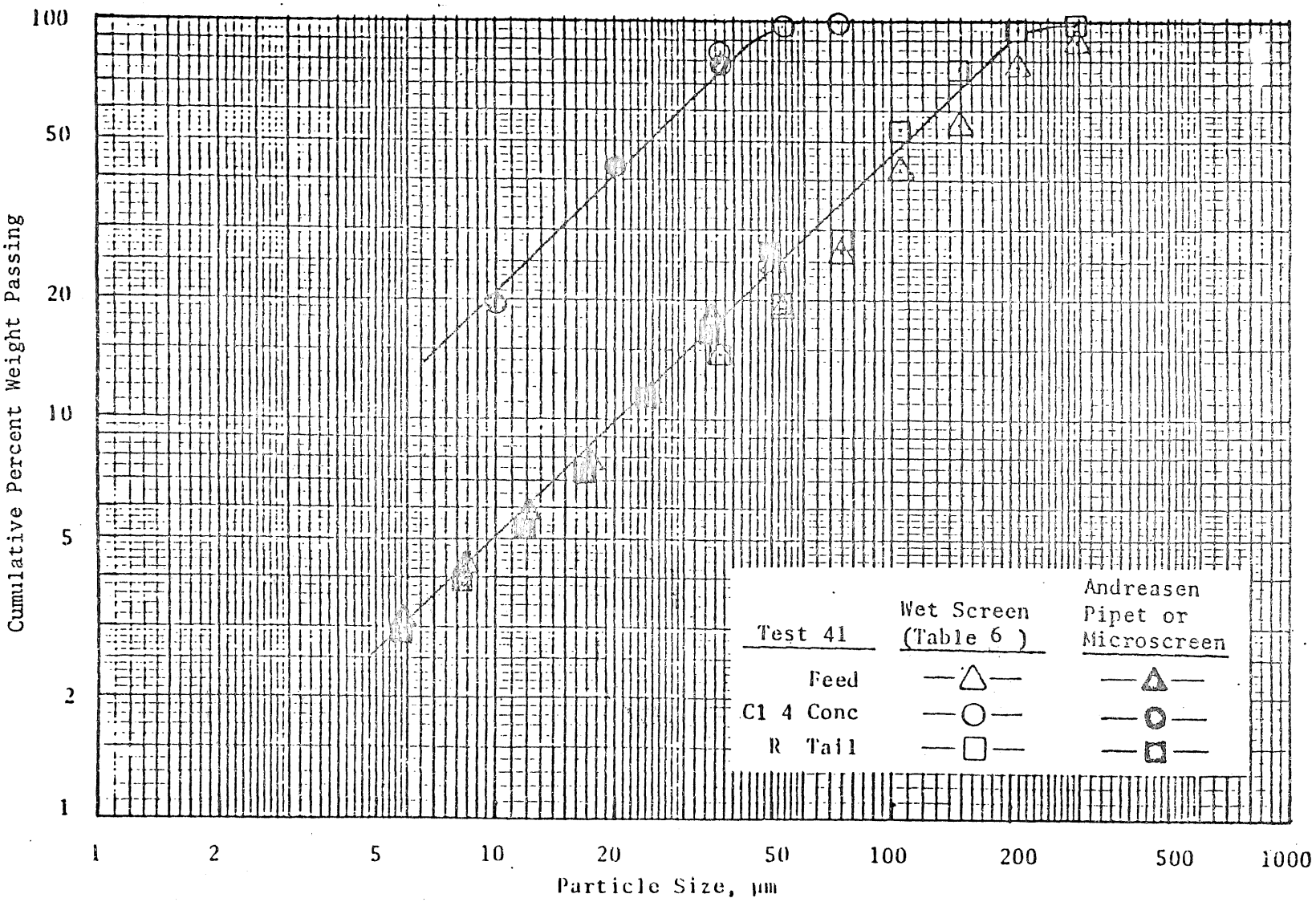


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF IP9002
(MINUS 65 MESH FOR FEED AND TAILING, MINUS 270 MESH FOR CONCENTRATE)

The size distributions of concentrates in the same range were determined by microscreening (Table 12). The data in the 'subsieve' range are of particular interest since the air-borne dusts are siad to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200-mesh grind would have about 4 percent by weight of minus 5-μm particles. At a 65-mesh grind, however, minus 5-μm particles would be about 2.5 percent. The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

To investigate how various elements are distributed over different size fractions in the 'subsieve' range the feed and the rougher tailing samples were separated into +20, 20/10, 10/5 and -5 μm fractions by the sedimentation sizing method, and the size distributions of the concentrates were determined by microscreeening to 10 μm. Each size fraction of the feed, concentrate and rougher tailing was analyzed by Barringer Research Ltd. and are given in Tables 13 and 14. Except for copper and nickel in the rougher tailing, heavy metals are seen to be, more or less, evenly distributed over all the sizes. The copper and nickel contents in the minus 5-μm fraction in the rougher tailing, particular in Table 14, are appreciably higher than the other fractions. It is noted that a similar trend was also noted for zinc. It is also noted in Table 13 that small amounts of arsenic, molybdenum and lead were present in the smaller size fractions of the flotation concentrate.

TABLE 12. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF IP9002

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 40 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	49.52	-
+20	77.84	23.11	85.27
+10	9.69	14.27	7.43
+5	5.28	13.10**	3.24
-5	7.19	-	4.07
	(b) Test 41 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	20.77	-
+20	90.75	36.18	92.40
+10	3.94	23.33	3.39
+5	1.71	19.72**	1.50
-5	3.60	-	2.71

* Cl 4 Conc and Regr Cl 4 Conc, respectively
**Minus 10 µm

TABLE 13. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT ON SIZE FRACTIONS OF FLOTATION PRODUCTS OF IP9002 (TEST 40 - ONE-STAGE GRIND FLOTATION)

	Feed				Concentrate				Rougher Tailing			
	+20 µm	20/10 µm	10/5 µm	-5 µm	+37 µm	37/20 µm	20/10 µm	-10 µm	+20 µm	20/10 µm	10/5 µm	-5 µm
Al	12.0	11.9	11.8	11.0	5.02	1.96	1.11	0.959	10.5	13.2	12.4	10.8
B	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Be	0.00006	0.00005	0.00006	0.00005	nd	nd	nd	nd	0.00006	0.00006	nd	0.00006
Ca	7.04	6.78	6.81	6.03	3.29	1.35	0.814	0.595	6.18	7.54	7.7	7.03
Cu	0.348	0.544	0.66	0.609	7.76	13.5	15.5	19.0	0.0377	0.0337	0.0541	0.0578
Fe	9.15	8.05	8.82	9.18	19.6	25.5	26.3	26.1	10.5	7.56	8.71	7.93
Mg	4.26	3.53	3.78	4.26	4.1	3.25	3.17	2.73	4.87	3.52	4.36	4.13
Mn	0.107	0.0864	0.0951	0.106	0.0763	0.0488	0.0418	0.0342	0.132	0.0899	0.104	0.106
P	nd	nd	nd	nd	nd	nd	nd	nd	0.016	0.01	0.02	0.012
Ba	0.183	0.0892	0.0767	0.0825	0.0062	0.0053	0.0057	0.0064	0.208	0.251	0.162	0.226
Se												
Te												
As	nd	nd	nd	nd	nd	nd	nd	0.005	nd	nd	nd	nd
Si	2.95	3.49	>3.52	>3.52	0.828	0.471	0.438	0.0971	3.11	>3.52	2.16	3.41
Sr	0.0368	0.0363	0.0357	0.0328	0.0129	0.00497	0.00273	0.00217	0.0318	0.042	0.0368	0.0358
Zr	0.00944	0.0104	0.0111	0.01	0.00337	0.00235	0.00227	0.00116	0.0107	0.011	0.0079	0.00966
Ti	0.459	0.412	0.457	0.417	0.121	0.0696	0.0495	0.0511	0.825	0.463	0.516	0.429
V	0.00937	0.00856	0.00895	0.00853	0.00852	0.00687	0.00629	0.00538	0.0116	0.00878	0.0103	0.00829
Zn	0.0087	0.0099	0.0108	0.0167	0.0183	0.031	0.0497	0.156	0.0121	0.0103	0.0138	0.0198
Th	0.0004	0.00041	0.00048	0.0004	0.00026	nd	nd	nd	0.00047	0.00048	0.0004	0.00034
K	0.489	0.527	0.539	0.696	0.165	0.039	0.017	0.008	0.46	0.555	0.458	0.846
Na	2.91	2.96	2.93	2.64	1.01	0.42	0.29	0.23	2.66	3.32	2.92	2.79
Cd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cr	0.0102	0.058	0.091	0.0612	0.00247	nd	0.00129	0.0218	0.0155	0.0488	0.0763	0.0582
Co	0.0092	0.0099	0.0099	0.0094	0.0768	0.148	0.16	0.132	0.0077	0.0046	0.0044	0.0046
Ag	0.00023	0.00025	0.00036	0.00059	0.00174	0.00284	0.0038	0.00615	0.00011	0.00012	0.00012	0.00014
Mo	nd	nd	0.0014	nd	nd	nd	nd	0.0006	nd	nd	nd	0.0014
Ni	0.0947	0.112	0.13	0.115	1.48	3.15	3.39	2.68	0.0325	0.027	0.035	0.0386
Pb	nd	nd	nd	nd	nd	0.0035	0.007	0.0225	nd	nd	nd	nd

TABLE 14. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT ON SIZE FRACTIONS OF FLOTATION PRODUCTS OF IP9002 (TEST 41 - TWO-STAGE GRIND FLOTATION)

	Feed				Concentrate				Rougher Tailing			
	+20 μm	20/10 μm	10/5 μm	-5 μm	+37 μm	37/20 μm	20/10 μm	-10 μm	+20 μm	20/10 μm	10/5 μm	-5 μm
Al	11.1	11.8	12.1	10.6					11.2	12.1	11.9	10.4
B	nd	nd	nd	nd					nd	nd	nd	nd
Be	nd	0.00005	nd	0.00005					0.00005	0.00006	0.00007	0.00006
Ca	6.34	6.49	6.6	6.32					6.43	6.85	6.97	6.19
Cu	0.483	0.723	0.582	0.693					0.0399	0.05	0.0875	0.237
Fe	9.43	8.34	7.84	9.38					9.55	8.59	9.16	9.37
Mg	4.22	3.46	3.24	4.28					4.44	3.59	3.88	4.26
Mn	0.12	0.881	0.855	0.11					0.11	0.0915	0.0982	0.116
P	nd	nd	nd	nd					0.022	0.021	0.021	nd
Ba	0.226	0.112	0.248	0.904					0.165	0.223	0.226	0.234
Se												
Te												
As	nd	nd	nd	nd					nd	nd	nd	nd
Si	3.45	3.26	2.94	2.75					2.44	3.32	3.40	> 3.52
Sr	0.0332	0.0351	0.0355	0.0298					0.0356	0.0386	0.0387	0.0321
Zr	0.0112	0.0115	0.0101	0.00869					0.00908	0.0121	0.0116	0.0105
Ti	0.551	0.434	0.397	0.397					0.569	0.48	0.489	0.416
V	0.00957	0.00865	0.00835	0.00885					0.0104	0.0108	0.011	0.00994
Zn	0.0091	0.01	0.0163	0.0201					0.0085	0.0108	0.0185	0.0267
Th	0.0004	0.00022	nd	0.00043					0.00048	0.00049	0.00064	0.00063
K	0.46	0.423	0.304	0.745					0.397	0.453	0.448	0.957
Na	2.76	2.74	2.7	2.4					2.67	2.96	2.89	2.38
Cd	nd	nd	nd	nd					nd	nd	nd	nd
Cr	0.0128	0.0638	0.0840	0.0649					0.0118	0.078	0.112	0.102
Co	0.0103	0.0111	0.008	0.011					0.0067	0.0048	0.0053	0.007
Ag	0.00022	0.00026	0.00007	0.00061					0.00014	0.00009	0.00015	0.00026
Mo	nd	nd	nd	nd					nd	0.002	0.0049	0.0123
Ni	0.117	0.175	0.159	0.157					0.0303	0.0364	0.055	0.0865
Pb	nd	nd	nd	nd					nd	nd	0.002	nd

3.2 FLOTATION TESTS ON IP9003 SAMPLE

Sample Description

An Inco Maturi shaft sample, weighing approximately 200 pounds, was received on September 17, 1968. The sample, which had been designated Ore No. 1669, Lot 2 at the Mineral Resources Research Center, was relabeled IP9003 in the present investigation. It was reported to have been obtained at depths of 798 to 905 feet from the exploration shaft.

The sample, already crushed to minus 1/2 inch, was further crushed in stages to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF IP9003 SAMPLE

Constituent	Percent
Copper (Cu)	0.69
Nickel (Ni)	0.205
Cobalt (Co)	0.015
Iron (Fe)	11.49
Sulfur (S)	1.27
Titanium dioxide (TiO_2)	0.73
Graphite carbon (C)	0.091

Grinding Characteristics

The grinding characteristics of the IP9003 sample were investigated by grinding 1200-gram batches of minus 10-mesh feed in a stainless steel laboratory rod mill at 50 percent solids for various periods of time. The size distributions of the minus 10-mesh feed and of a sample ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. The

TABLE 2. SCREEN ANALYSIS OF IP9003 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	0.3	100.0	-	-	-	-	-	-	-	-
+14	12.9	99.7	-	-	-	-	-	-	-	-
+20	9.8	86.8	-	-	-	-	-	-	-	-
+28	21.5	77.0	-	-	-	-	-	-	-	-
+35	9.9	55.5	-	-	-	-	-	-	-	-
+48	8.5	45.6	2.9	100.0	0.3	100.0	-	-	-	-
+65	7.6	37.1	6.3	97.1	3.4	99.7	0.1	100.0	-	-
+100	7.5	29.5	23.2	90.8	16.8	96.3	3.6	99.9	-	-
+150	5.0	22.0	15.7	67.6	19.5	79.5	20.2	96.3	0.3	100.0
+200	6.9	17.0	18.2	51.9	16.0	60.0	26.0	76.1	7.6	99.7
+270	2.7	10.1	6.3	33.7	11.2	44.0	11.2	50.1	18.5	92.1
+325	0.9	7.4	3.8	27.4	4.8	32.8	5.9	38.9	12.8	73.6
+400	0.6	6.5	2.8	23.6	3.0	28.0	3.0	33.0	10.8	60.8
+500	2.1	5.9	4.9	20.8	5.0	25.0	6.0	30.0	11.0	50.0
-500	3.8	3.8	15.9	15.9	20.0	20.0	24.0	24.0	39.0	39.0

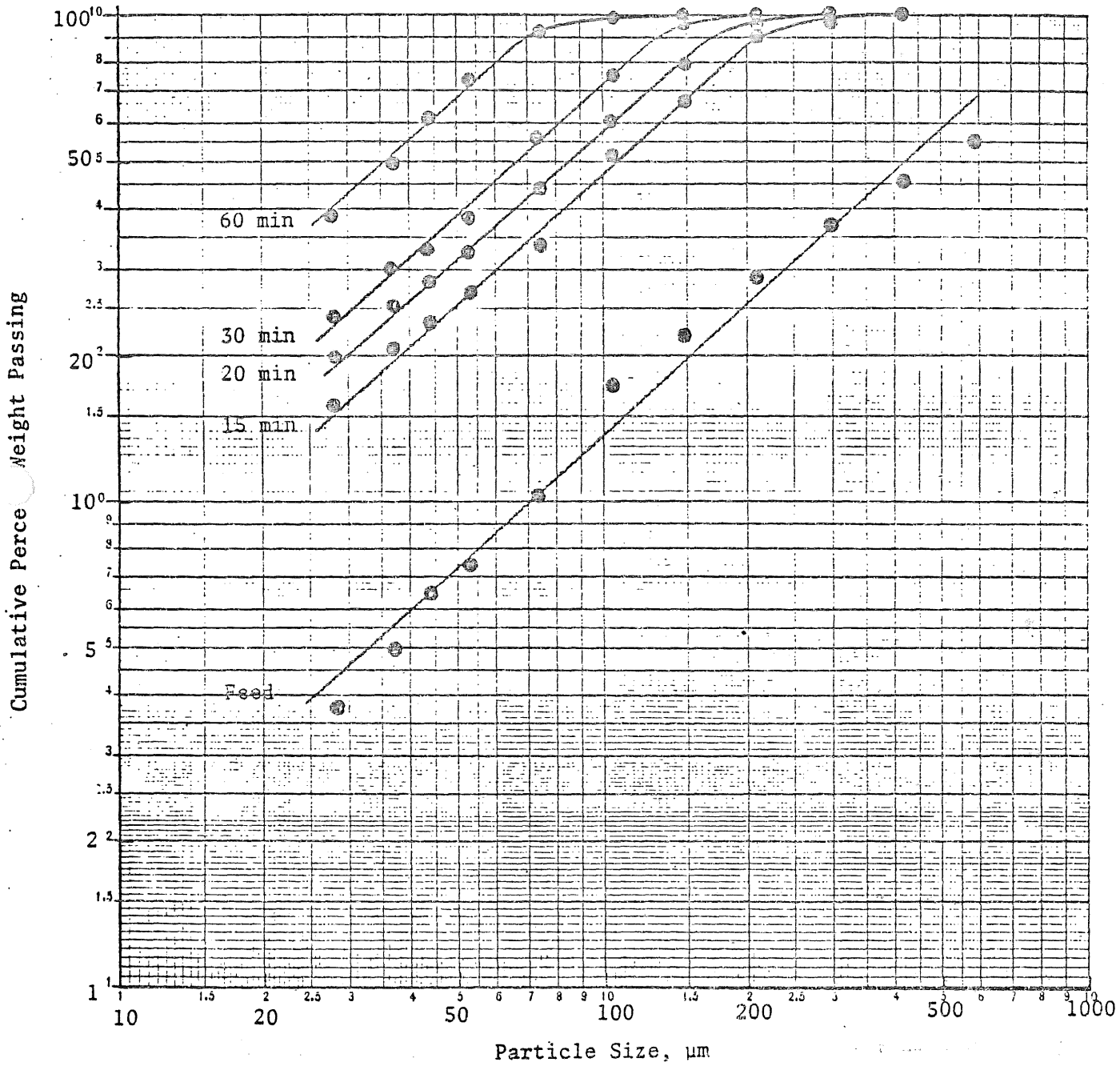


FIGURE 1. SIZE DISTRIBUTIONS OF IP9003 SAMPLE AS A FUNCTION OF GRINDING TIME

size distribution data of the ground batches are seen to be represented by straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.89. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF IP9003 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50 PERCENT SOLIDS)

Nominal Mesh-of-Grind	Grind Time Minutes	Size Modulus k, μm	80% passing μm
-10 mesh	0	-	930
-48 mesh	15	230	182
-65 mesh	20	187	145
-100 mesh	30	145	113
-200 mesh	60	78	61

Preliminary Flotation Tests

The effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh, and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed also at 3 minutes. The results of these flotation tests are given in Table 4.

TABLE 4. EFFECT OF MESH-OF-GRIND ON IP9003

Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Cleaner - MIBC 0.06 lb/ton

Flotation Time: Rougher 10 min, Cleaner 5 min

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	2.30	18.00	3.06	65.96	35.77	2.30	18.00	3.06	65.96	35.77
		Cl 4 Tail	0.17	2.05	2.05	2.82	2.64	2.47	17.48	3.06	68.78	38.41
		Cl 3 Tail	0.92	1.85	1.87	6.75	8.74	3.39	13.99	2.74	75.53	47.15
		Cl 2 Tail	1.81	1.14	1.14	7.75	10.47	5.20	10.05	2.18	83.28	57.62
		Cl 1 Tail	4.79	0.38	0.38	6.09	9.45	9.99	5.62	1.32	89.37	67.07
		R Tail	90.01	0.074	0.072	10.63	32.93	100.00	0.63	0.197	100.00	100.00
2	65	Cl 4 Conc	2.73	17.14	3.17	71.25	42.34	2.73	17.14	3.17	71.25	42.34
		Cl 4 Tail	1.05	3.99	2.05	6.38	10.52	3.78	13.49	2.86	77.63	52.34
		Cl 3 Tail	0.50	3.00	0.80	2.28	1.96	4.28	12.26	2.62	79.91	54.82
		Cl 2 Tail	2.35	1.98	0.62	7.08	7.15	6.63	8.62	1.91	86.99	61.97
		Cl 1 Tail	5.67	0.50	0.21	4.32	5.83	12.30	4.88	1.13	91.32	67.80
		R Tail	87.70	0.065	0.075	8.68	32.20	100.00	0.66	0.204	100.00	100.00
3	100	Cl 4 Conc	2.49	19.19	3.84	73.91	41.57	2.49	19.19	3.84	73.91	41.57
		Cl 4 Tail	0.74	2.58	3.66	2.95	11.79	3.23	15.38	3.80	76.86	53.36
		Cl 3 Tail	1.80	2.53	1.26	7.04	9.88	5.03	7.12	2.89	83.90	63.24
		Cl 2 Tail	2.59	1.26	0.47	5.04	5.31	7.62	7.55	2.00	88.94	68.55
		Cl 1 Tail	8.44	0.29	0.16	3.79	5.87	16.06	3.73	1.07	92.73	74.42
		R Tail	83.94	0.056	0.07	7.27	25.58	100.00	0.65	0.23	100.00	100.00
4	200	Cl 4 Conc	3.34	15.68	3.76	76.16	55.53	3.34	15.68	3.76	76.16	55.53
		Cl 4 Tail	0.25	5.52	1.63	2.01	1.81	3.59	14.97	3.61	78.17	57.34
		Cl 3 Tail	1.21	2.45	1.06	4.32	5.66	4.80	11.82	2.97	82.49	63.00
		Cl 2 Tail	2.92	1.19	0.46	5.06	5.92	7.72	7.80	2.02	87.55	68.92
		Cl 1 Tail	13.85	0.21	0.123	4.23	7.52	21.57	2.93	0.80	91.78	76.44
		R Tail	78.43	0.072	0.068	8.22	23.56	100.00	0.69	0.23	100.00	100.00
5	Rghr 65	Regr Cl 4 C	2.16	21.68	3.44	74.37	36.36	2.16	21.68	3.44	74.37	36.36
	Regr 270	Regr Cl 4 T	0.13	4.20	3.87	0.84	2.45	2.29	20.69	3.46	75.21	38.81
		Regr Cl 3 T	0.11	3.05	1.45	0.54	0.78	2.40	19.88	3.37	75.75	39.59
		Regr Cl 2 T	0.58	3.40	2.79	3.13	7.93	2.98	16.67	3.26	78.88	47.52
		Regr Cl 1 T	2.39	2.17	1.35	8.24	15.81	5.37	10.21	2.41	87.12	63.33
		Cl Tail	4.57	0.75	0.26	5.45	5.83	9.94	5.87	1.42	92.57	69.16
		R Tail	90.06	0.052	0.07	7.43	30.84	100.00	0.63	0.204	100.00	100.00

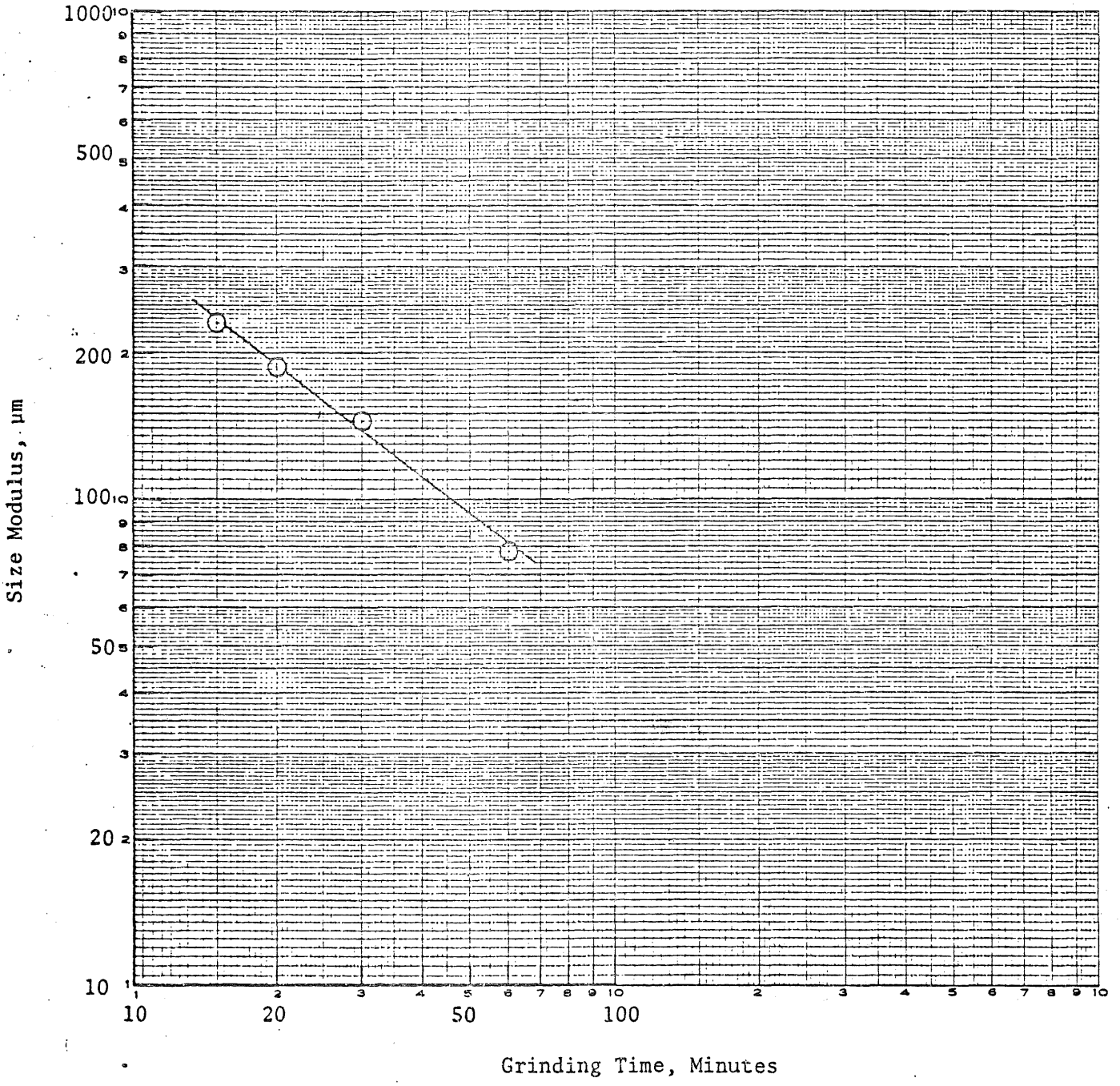


FIGURE 2. SIZE MODULI OF IP9003 SAMPLE AS A FUNCTION OF GRINDING TIME

It is apparent in Table 4 that both the losses of copper and of nickel to the R Tails reached plateaus at about 8 percent and 25 percent, respectively, for minus 100- and 200-mesh grind samples. The loss of copper to R Tails tended to increase somewhat at 65 mesh and noticeably at 48 mesh. It is also noted that the concentrates after three cleaner stages analyzed in excess of 15 percent copper and 3 percent nickel.

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 92.09%, 74.09%, and 93.31%, respectively, at 200 mesh (one-stage grind flotation), and were 91.89%, 65.51%, and 84.57%, respectively, at 65 mesh (two-stage grind flotation). The flotation concentrate could be upgraded to 17.17 percent copper and 3.34 percent nickel in the one-stage grind flotation after three cleanings, whereas in the two-stage grind flotation the concentrate was upgraded to 15.77 percent copper and 3.35 percent nickel after one cleaning following regrinding. The sum of the copper, nickel, cobalt, iron, and sulfur contents may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The third cleaner concentrate (Cl 3 Conc) in the one-stage grind flotation would then have 20.2 percent gangue and the reground first cleaner concentrate (Regr Cl 1 Conc) in the two-stage grind flotation would have 22.6 percent gangue.

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON IP9003

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 6 Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 24°C Rougher pH: 8.3							
Cl 4 Conc	3.13	17.50	3.40	0.12	33.62	26.30	0.19
Cl 4 Tail	0.08	3.99	1.07	0.048	18.20	7.45	-
Cl 3 Tail	1.25	2.58	1.80	0.070	22.94	11.04	-
Cl 2 Tail	2.59	1.00	0.41	0.022	14.00	3.10	-
Cl 1 Tail	11.87	0.27	0.145	0.017	10.27	0.69	-
R Tail	81.08	0.068	0.068	0.015	10.25	0.10	-
Flotation Feed	100.00	0.72	0.21	0.015	11.15	1.18	0.10
Test No. 7 Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 24°C Rougher pH: 8.0							
Regr Cl 4 C	2.32	19.96	3.56	0.164	34.92	30.73	0.19
Regr Cl 4 T	0.07	4.32	2.40	0.125	11.14	12.59	-
Regr Cl 3 T	0.11	3.00	1.67	0.090	18.92	9.38	-
Regr Cl 2 T	0.62	3.65	2.95	0.132	24.86	14.47	-
Regr Cl 1 T	1.90	1.74	0.80	0.040	15.63	6.43	-
Cl Tail	4.60	0.83	0.31	0.025	11.50	2.11	-
R Tail	90.38	0.055	0.078	0.019	10.25	0.21	-
Flotation Feed	100.00	0.66	0.21	0.028	11.45	1.25	0.08

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON IP9003

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 6 One-stage Grind Flotation																	
Cleaner 4	3.13	17.50	3.40	0.120	33.62	26.30	78.66	50.02	19.45	9.33	68.02	96.87	0.153	0.110	0.016	10.53	0.400
Cleaner 3	3.21	17.17	3.34	0.120	33.33	25.83	79.12	50.44	19.64	9.51	68.52	96.79	0.150	0.109	0.016	10.52	0.394
Cleaner 2	4.46	13.08	2.91	0.106	30.49	21.68	83.76	61.02	24.25	12.09	79.92	95.54	0.118	0.087	0.015	10.35	0.254
Cleaner 1	7.05	8.64	1.99	0.076	24.40	14.85	87.48	66.00	27.32	15.29	86.53	92.95	0.094	0.078	0.015	10.25	0.175
Rougher	18.92	3.39	0.83	0.039	15.54	5.97	92.09	74.09	37.56	26.13	93.31	81.08	0.068	0.068	0.015	10.25	0.100
Test No. 7 Two-stage Grind Flotation																	
Regr Cleaner 4	2.32	19.96	3.56	0.164	34.92	30.73	75.55	40.41	15.85	7.32	57.93	97.68	0.153	0.125	0.021	10.51	0.530
Regr Cleaner 3	2.39	19.50	3.53	0.163	34.31	30.21	76.04	41.24	16.23	7.43	58.66	97.61	0.151	0.123	0.021	10.51	0.522
Regr Cleaner 2	2.50	18.78	3.44	0.159	33.60	29.28	76.58	42.12	16.61	7.59	59.47	97.50	0.147	0.121	0.021	10.50	0.512
Regr Cleaner 1	3.12	15.77	3.35	0.153	31.73	26.35	80.26	51.07	19.95	8.94	66.78	96.88	0.125	0.103	0.020	10.42	0.422
Cleaner	5.02	10.46	2.38	0.111	25.70	18.81	85.66	58.51	23.29	11.65	76.69	94.98	0.093	0.089	0.019	10.31	0.302
Rougher	9.62	5.86	1.39	0.071	18.92	10.82	91.89	65.51	28.29	16.43	84.57	90.38	0.055	0.078	0.019	10.25	0.210

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF IP9003

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+150	0.71	-	0.98
+200	10.91	2.21	11.42
+270	24.61	11.03	25.55
+400	20.80	20.22	22.57
-400	42.97	66.54	39.48
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	0.20	-	0.86
+65	5.14	-	7.38
+100	18.23	-	27.96
+150	27.40	-	25.50
+200	15.13	0.70	15.80
+270	7.78	2.10	6.31
+400	7.42	7.69	4.74
-400	18.70	89.51	11.45

*Cl 4 Conc and Regr Cl 4 Conc, respectively

A Davis magnetic tube test was performed on a Cl 4 Conc sample to explore the feasibility of a copper-nickel separation, but the magnetic concentrate amounted to only 0.89 percent by weight. Hence, chemical analyses on the magnetic separation products were not made. Evidently, the pyrrhotite in the present sample is the nonmagnetic variety.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, Cl Tail, and R Tail samples in both the one-stage grind flotation test and in the two-stage grind flotation test were analyzed by Barringer Research Ltd. The results are given in Tables 7 and 8. In these tables it is seen that the concentration of such trace elements as silver and lead in the cleaner concentrates increased to some extent. These increases are apparently due to the close association of these elements with sulfide minerals. The copper, nickel, iron and cobalt analyses by Barringer and by the MRRC are seen to be in reasonably good agreement. The silicon analyses in Table 7 and 8 appear to be unreasonably low since the feed and tailing samples were essentially silicates.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were taken in a similar manner after one week and one month of standing, but the analyses of these solution samples for trace elements were withheld since all the other samples showed virtually identical trends. The

TABLE 7. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON IP9003 (TEST 6 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	9.17		1.67		9.44		9.36	
B	0.266		0.0994		0.258		0.279	
Be	0.00003		nd		0.00004		0.00003	
Ca	5.48		1.11		5.58		5.54	
Cu	0.532	0.72	14.7	17.50	0.284	0.27	0.034	0.068
Fe	8.87	11.15	30.9	33.62	8.48	10.27	8.39	10.25
Mg	5.69		1.83		5.13		5.69	
Mn	0.0982		0.0253		0.0962		0.111	
P	nd		nd		nd		0.01	
Ba	0.18		0.0174		0.175		0.186	
Se	nd		nd		nd		nd	
Te	0.233		0.567		0.132		0.217	
As	nd		nd		nd		nd	
Si	2.97		0.671		2.84		2.97	
Sr	0.0306		0.00541		0.031		0.0313	
Zr	0.0093		0.0029		0.0087		0.0093	
Ti	0.594		0.0658		0.545		0.663	
V	0.0101		0.00184		0.00805		0.011	
Zn	0.0079		0.0028		0.0089		0.0083	
Th	nd		nd		nd		nd	
K	0.34		0.03		0.367		0.34	
Na	2.26		0.402		2.27		2.35	
Cd	nd		nd		nd		nd	
Cr	0.0672		0.0143		0.113		0.0637	
Co	0.0105	0.015	0.0997	0.12	0.0089	0.017	0.007	0.015
Ag	nd		0.0037		nd		nd	
Mo	0.001		nd		0.0032		0.0007	
Ni	0.158	0.21	2.93	3.40	0.125	0.145	0.053	0.068
Pb	nd		0.0013		nd		nd	

*Conventional AA analyses

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON IP9003 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	9.06		0.804		9.22		9.46	
B	0.245		0.0619		0.265		0.263	
Be	0.00003		nd		0.00004		0.00003	
Ca	5.46		0.537		5.53		5.68	
Cu	0.588	0.66	18.2	19.96	0.755	0.83	0.0665	0.055
Fe	9.14	11.45	33.9	34.92	9.21	11.50	8.31	10.25
Mg	5.65		1.38		4.68		5.69	
Mn	0.105		0.0161		0.0882		0.111	
P	nd		nd		nd		nd	
Ba	0.162		0.0147		0.165		0.175	
Se	nd		nd		nd		nd	
e	0.233		0.567		0.233		0.233	
As	nd		nd		nd		nd	
Si	2.59		0.259		2.58		2.81	
Sr	0.0299		0.0024		0.0299		0.0312	
Zr	0.0084		0.0017		0.0093		0.0086	
Ti	0.639		0.0362		0.495		0.613	
V	0.0104		0.00089		0.00828		0.0107	
Zn	0.0082		0.0017		0.0113		0.0081	
Th	nd		nd		nd		nd	
K	0.326		nd		0.417		0.347	
Na	2.22		0.216		2.1		2.32	
Cd	nd		nd		nd		nd	
Cr	0.0405		0.00932		0.0798		0.0353	
Co	0.0113	0.028	0.102	0.16	0.0131	0.025	0.0074	0.019
Ag	nd		0.0042		0.0008		nd	
Mo	nd		nd		0.0032		0.0004	
Ni	0.17	0.21	3.08	3.56	0.26	0.31	0.0589	0.078
Pb	nd		0.003		nd		nd	

*Conventional AA analyses

tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 9 shows the amounts of residual flotation reagents in the liquors. Tables 10 and 11 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease somewhat from near 8 immediately after flotation to about 7.8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed almost completely in one week. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors. Of particular interest in Table 11 is the fact that the concentrations of copper and nickel ions in the feed water were rather high, 31 and 480 ppb, respectively, and that the concentration of copper decreased to 19 ppb and the concentration of nickel to below the limit of detection (90 ppb) during flotation. The high initial concentrations of these ions must have been caused by the oxidation of sulfide minerals in storage over 10 years. The decrease in their concentrations in the presence of the ore sample may be interpreted to be due to adsorption and that upon the addition of flotation reagents to the precipitation of insoluble copper and nickel xanthates. The zinc-ion concentration amounted to a few hundredths to a few tenths of one ppm in a month. Perhaps the zinc ions might have been released by the exchange reaction with copper and nickel ions.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of Table 6. The size distributions of concentrates in the same range were determined by microscreening (Table 12). The data in the 'subsieve' range are of particular interest since the air-borne dusts are said to be typically in the range of

TABLE 9. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTION OF IP9003

Sampling Time	One-stage Grind Flotation (Test 6)			Two-stage Grind Flotation (Test 7)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	8.0	0.35	6.84	7.9	0.43	10.00
After 1 Day	8.0	0.29	3.53	7.8	0.38	3.34
After 1 Week	7.8	0.25	0.00	7.8	0.24	0.00
After 1 Month	7.9	0.23	0.00	7.8	0.12	0.00

TABLE 10. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF IP9003 (TEST 6 - MINUS 200 MESH GRIND)

	Feed Water	Tailing Water			
		immed.	1 day old	1 week old	1 month old
Al		0.3			
B		nd			
Ba		0.05			
Be		nd			
Ca		51.5			
Cu		0.019			
Fe		0.057			
K		6.7			
Mg		23.5			
Mn		0.0336			
Na		12			
P		nd			
Se		5			
Te		nd			
Pb		nd			
Si		2.42			
Sr		0.0804			
Sr		0.003			
V		0.029			
Zn		0.07			
Th		0.02			
Ag		nd			
As		nd			
Cd		nd			
Co		nd			
Cr		0.085			
Mo		0.03			
Ni		0.11			
Zr		nd			

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF IP9003 (TEST 7 - MINUS 65 MESH GRIND)

	Feed Water	Tailing Water			
		immed.	1 day old	1 week old	1 month old
Al	0.38	0.36			
B	10.0	10.0			
Ba	0.05	0.05			
Be	nd	nd			
Ca	131	71.4			
Cu	0.031	0.019			
Fe	0.162	0.176			
K	6.7	8.0			
Mg	41.4	38.1			
Mn	0.12	0.0444			
Na	20	15			
P	nd	nd			
Se	nd	nd			
Te	nd	nd			
Pb	nd	nd			
Si	2.08	2.5			
Sr	0.193	0.11			
Ti	0.005	0.003			
V	0.05	0.034			
Zn	0.07	0.16			
Th	0.06	0.026			
Ag	nd	nd			
As	nd	nd			
Cd	nd	nd			
Co	nd	nd			
Cr	0.149	0.104			
Mo	0.08	0.12			
Ni	0.48	nd			
Zr	nd	nd			

TABLE 12. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF IP9003

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	22.59	-
+20	87.93	30.43	89.86
+10	5.72	24.08	5.42
+5	2.76	22.90**	2.06
-5	3.59	-	2.66
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	15.28	-
+20	92.25	24.41	94.98
+10	3.42	15.74	2.22
+5	1.93	44.57**	1.12
-5	2.40	-	1.68

* C1 4 Conc and Regr C1 4 Conc, respectively
**Minus 10 µm

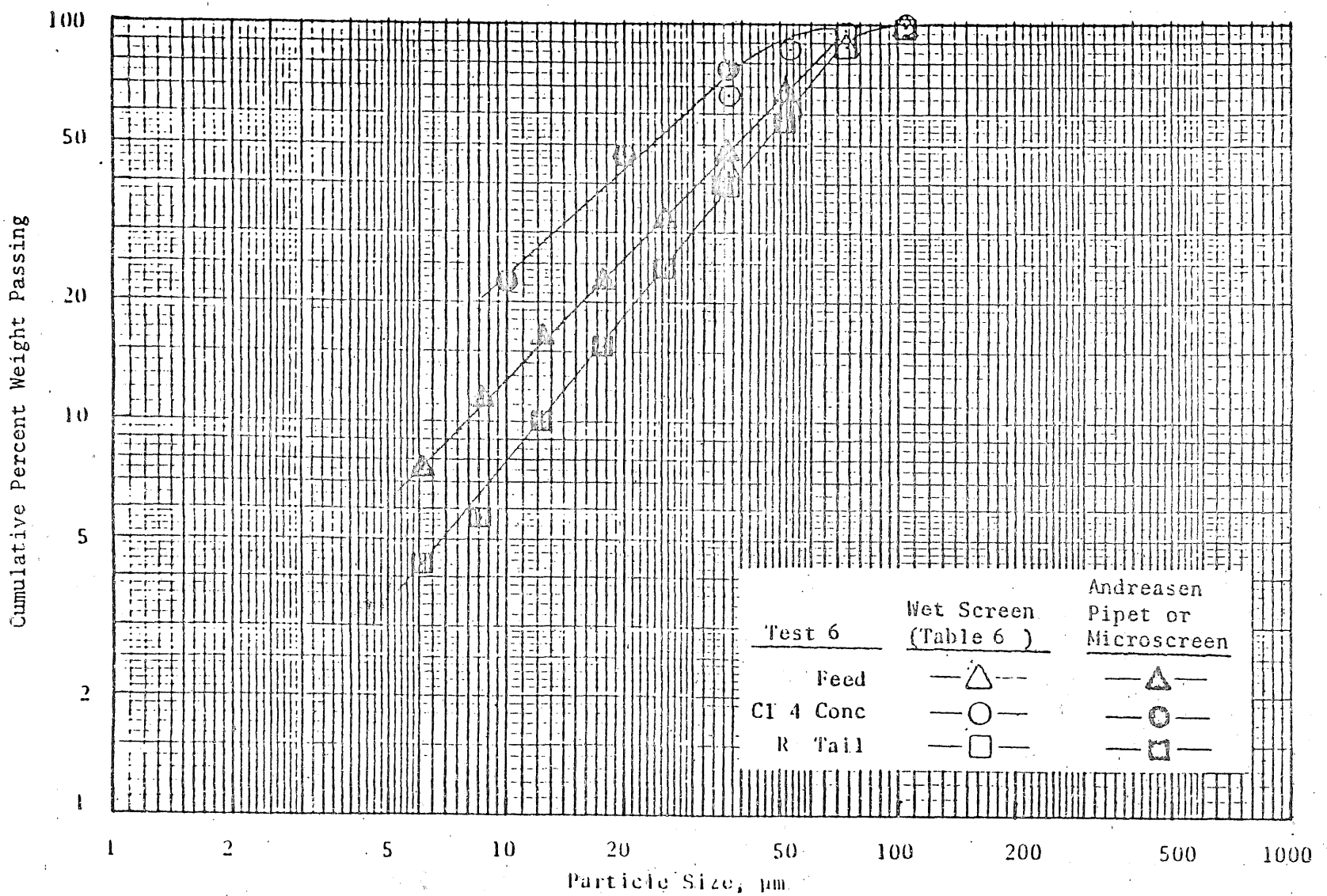


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF IP9003 (MINUS 200 MESH GRIND)

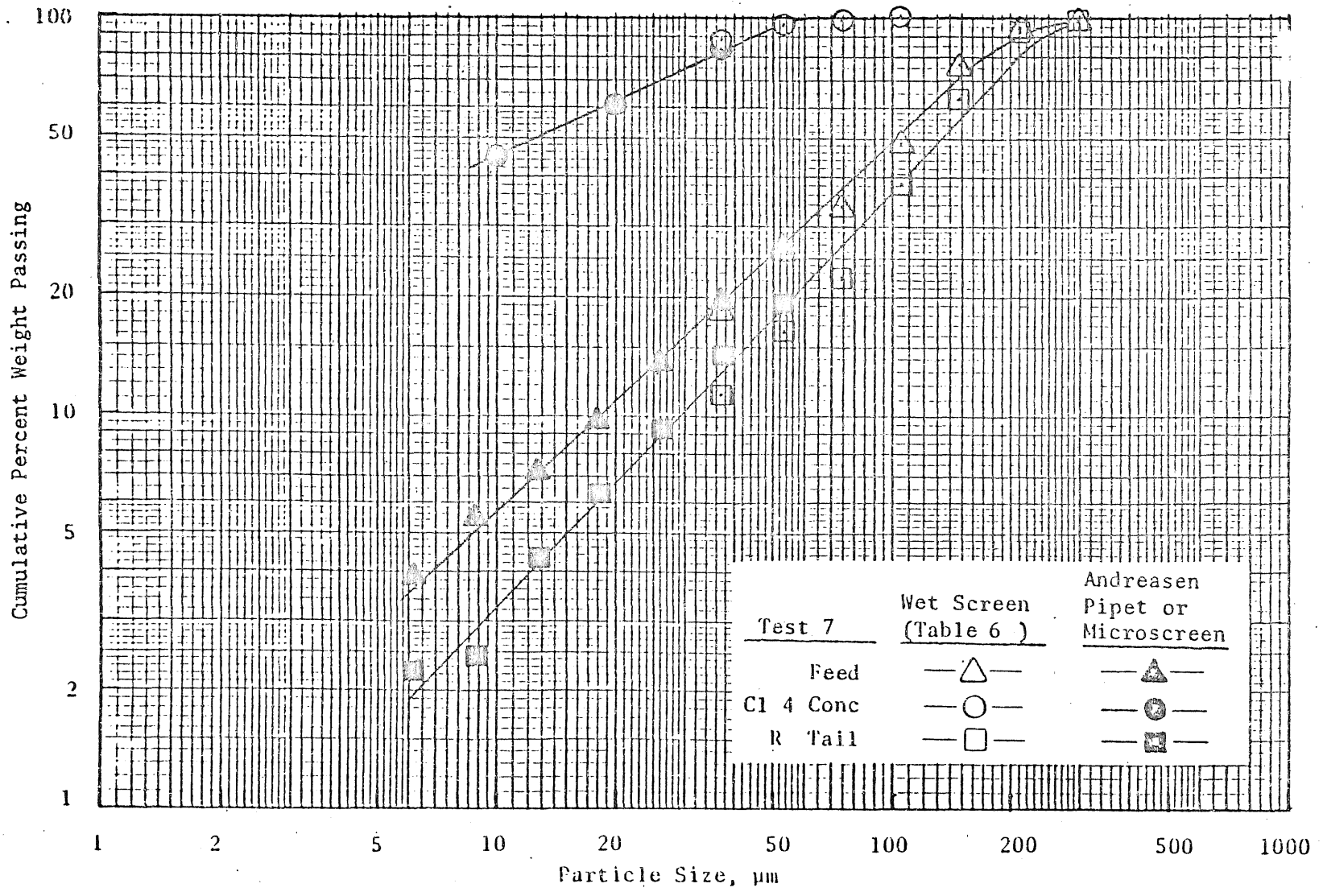


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF IP9003
(MINUS 65 MESH FOR FEED AND TAILING, MINUS 270 MESH FOR CONCENTRATE)

5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200-mesh grind would have about 3 percent by weight of minus 5-μm particles. At a 65-mesh grind, however, minus 5 μm particles would be about 1.5 percent. The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

3.3 FLOTATION TESTS ON DP9002 SAMPLE

Sample Description

A Dunka River mineralized gabbro sample, labeled DP9002, weighing approximately 275 kilograms, was received on May 5, 1977, from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. This mineralized gabbro sample was reported to be picked from a gabbro stockpile east of the northern extension of the Dunka Pit in Section 3, Township 60N, Range 12W. Only those pieces showing mineralization were taken for mineralogical characterization and flotation testing.

The whole sample received was stage-crushed to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF DP9002 SAMPLE

Constituent	Percent
Copper (Cu)	0.81
Nickel (Ni)	0.25
Cobalt (Co)	0.037
Iron (Fe)	15.03
Sulfur (S)	3.93
Titanium dioxide (TiO_2)	2.39
Graphite carbon (C)	0.066

Grinding Characteristics

The grinding characteristics of the crude sample were investigated by determining the size distribution of a 1200-gram lot ground in a stainless

steel laboratory rod mill at 50 percent solids. The size distributions of the minus 10-mesh feed and of a sample ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. The size distribution data of the ground samples are seen to follow straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.94. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding time-of-grind in Figure 2. In the figure the experimental points of IP9002 Sample are also included. It is evident that these two sets of points are represented by different straight lines. The grinding characteristics of these two Duluth gabbro samples, therefore, are different. Nevertheless, the samples ground for 15, 20, 30 and 60 minutes were taken as nominally minus 48, 65, 100 and 200-mesh grinds. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80-percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF DP9002 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50% SOLIDS)

Nominal Mesh-of-Grind	Grind Time Minutes	Size Modulus k, μm	80% passing μm
-10 mesh	0	-	1070
-48 mesh	15	255	205
-65 mesh	20	170	135
-100 mesh	30	105	84
-200 mesh	60	55	44

TABLE 2. SCREEN ANALYSIS OF DP9002 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	0.2	100.0	-	-	-	-	-	-	-	-
+14	17.7	99.8	-	-	-	-	-	-	-	-
+20	11.8	82.1	-	-	-	-	-	-	-	-
+28	21.7	70.3	-	-	-	-	-	-	-	-
+35	10.1	48.6	0.2	100.0	-	-	-	-	-	-
+48	7.3	38.5	5.0	99.8	2.0	100.0	-	-	-	-
+65	5.8	31.2	14.0	94.8	5.0	98.0	-	-	-	-
+100	5.9	25.4	19.4	80.8	9.7	93.0	2.1	100.0	-	-
+150	4.2	19.5	15.8	61.4	19.3	83.3	8.9	97.9	-	-
+200	5.8	15.3	14.5	45.6	19.0	64.0	18.5	89.0	1.7	100.0
+270	3.3	9.5	8.6	31.1	12.4	45.0	19.5	70.5	8.7	98.3
+325	0.9	6.2	4.5	22.5	5.6	32.6	8.2	51.0	9.1	89.6
+400	0.6	5.3	2.4	18.0	4.2	27.0	6.8	42.8	13.2	80.5
+500	2.2	4.7	4.2	15.6	5.0	22.8	8.5	36.0	15.5	67.3
-500	2.5	2.5	11.4	11.4	17.8	17.8	27.5	27.5	51.8	51.8

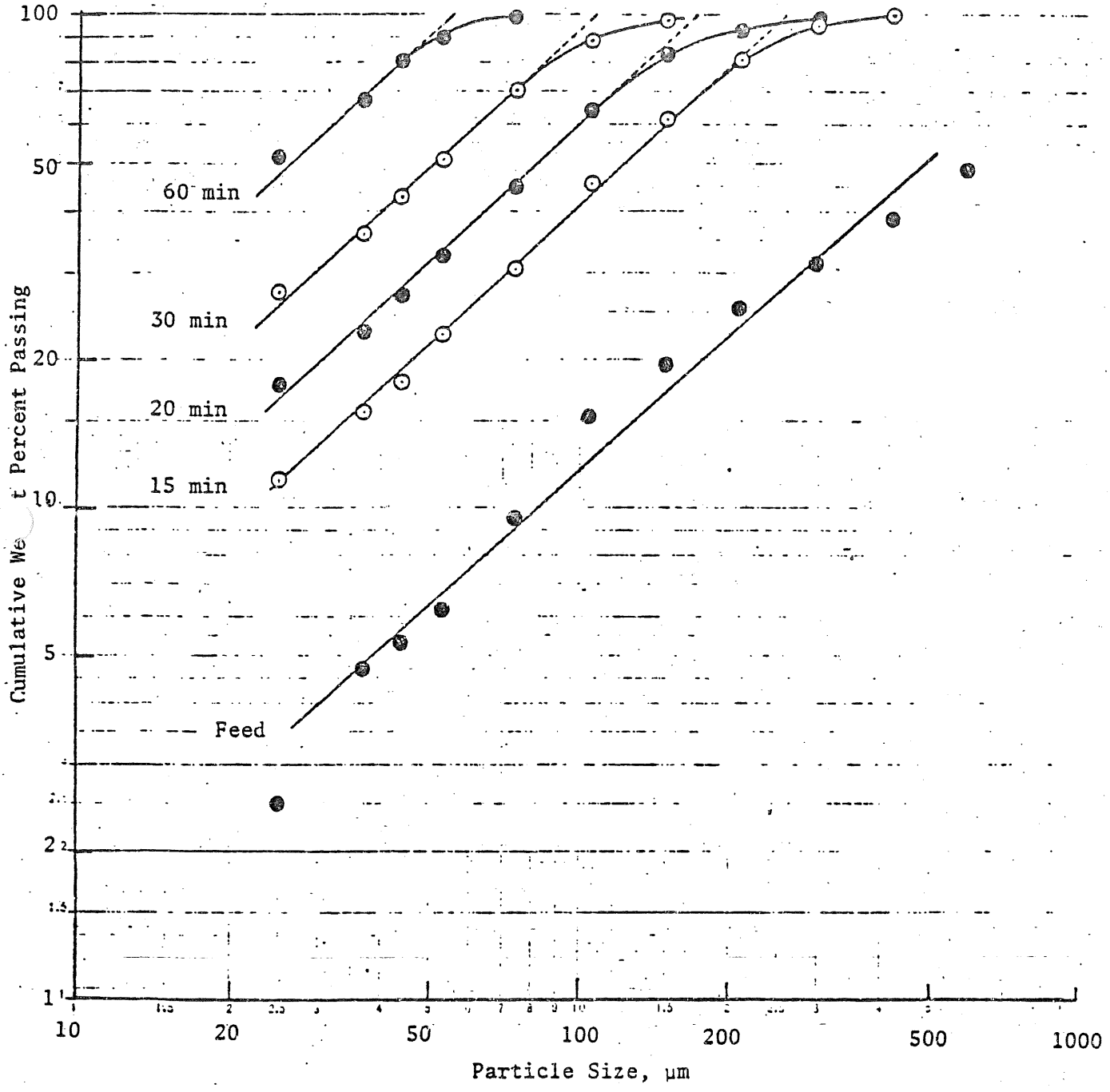


FIGURE 1. SIZE DISTRIBUTION OF DP9002 SAMPLE AS A FUNCTION OF GRINDING TIME

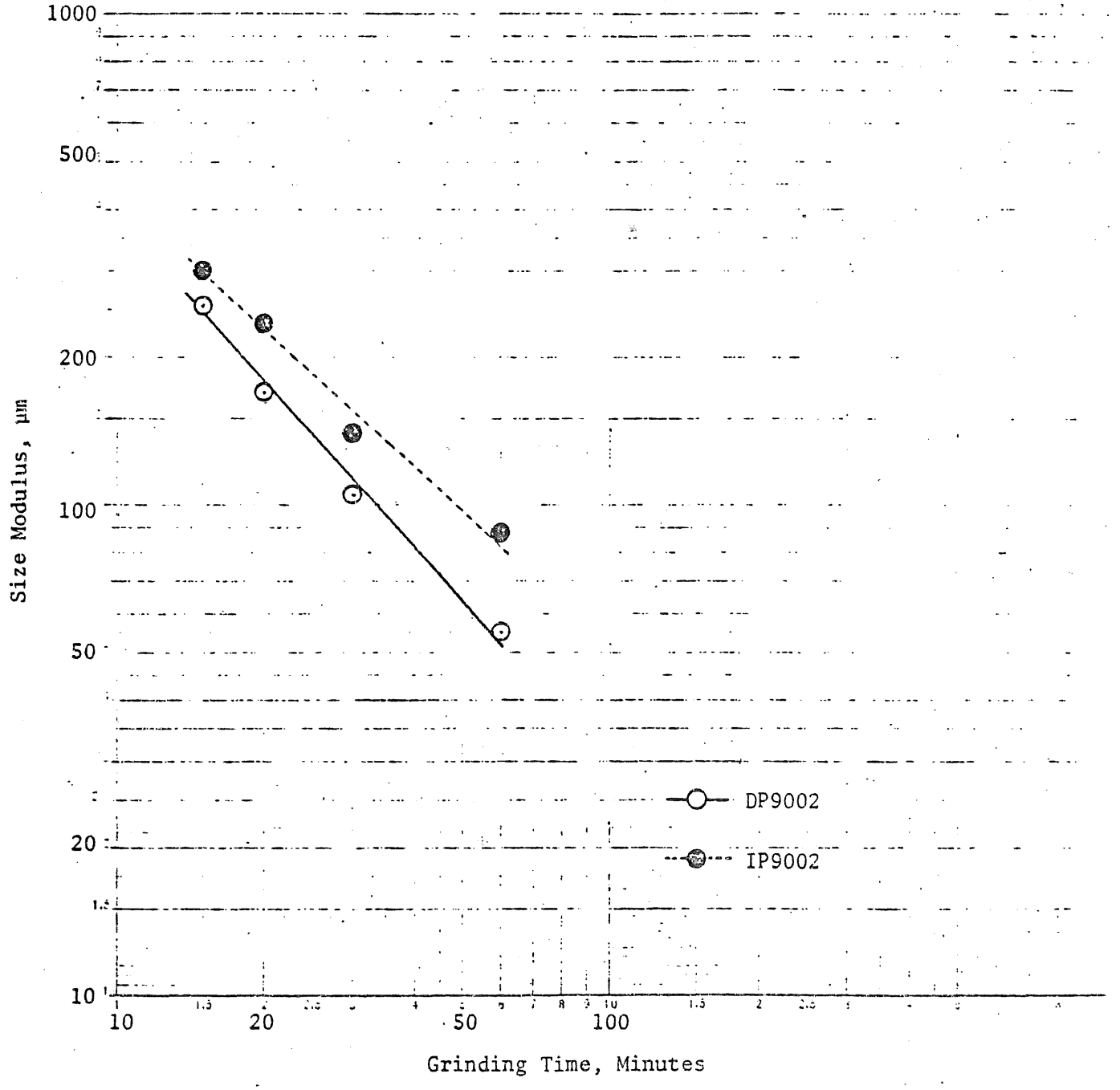


FIGURE 2. SIZE MODULUS OF DP9002 AND IP9002 SAMPLES AS A FUNCTION OF GRINDING TIME

Preliminary Flotation Tests

Initially the effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 lb of KAX per ton for 2 minutes and then with 0.05 lb of MIBC per ton for one minute. The rougher flotation time was fixed at 10 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed at 5 minutes. The results of these flotation tests are given in Table 4.

The effect of the mesh-of-grind, judged from the copper and nickel analysis data of rougher tailings (R Tail), shows that the losses of copper and nickel reach plateaus at 3 to 4 percent and about 13 percent, respectively, for minus 100-mesh and 200-mesh grind samples. The losses of copper and nickel to R Tails increased somewhat at 65 mesh and noticeably at 48 mesh. Though these observations are quite similar to those made on the AX9002 and IP9002 samples, their losses to R Tails are about half as much as those on the AX9002 and IP9002 samples. It should be noted here that the copper and nickel analyses of R Tails are 0.04 percent, about the same as the analyses of the other two gabbro samples. The lower losses to R Tails (or higher recoveries to concentrates) may be attributable to the higher head analysis of the present sample.

Table 4 includes the results of a two-stage grind flotation test. It is interesting to note that after regrinding there was no difficulty in achieving a concentrate grade in excess of 14 percent copper. It appears, therefore, that the two-stage grind flotation had a definite advantage over the one-stage grind flotation in achieving the grade of concentrate.

TABLE 4. EFFECT OF MESH-OF-GRIND ON DP9002

Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Cleaner - MIBC 0.06 lb/ton

Flotation Time: Rougher 10 min, Cleaner 5 min

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	8.02	7.95	1.96	83.78	70.18	8.02	7.95	1.96	83.78	70.18
		Cl 4 Tail	0.43	0.71	0.50	0.41	0.98	8.45	7.58	1.89	84.19	71.16
		Cl 3 Tail	1.40	0.80	0.40	1.47	2.50	9.85	6.62	1.68	85.66	73.66
		Cl 2 Tail	1.59	0.55	0.25	1.16	1.79	11.44	5.78	1.48	86.82	75.45
		Cl 1 Tail	5.40	0.18	0.095	1.28	2.28	16.84	3.98	1.03	88.10	77.73
		R Tail	83.16	0.109	0.06	11.90	22.27	100.00	0.76	0.224	100.00	100.00
2	65	Cl 4 Conc	7.18	9.96	2.22	88.86	76.74	7.18	9.96	2.22	88.86	76.74
		Cl 4 Tail	0.27	1.09	1.11	0.36	1.44	7.45	9.64	2.18	89.22	78.18
		Cl 3 Tail	1.34	0.97	0.60	1.62	3.85	8.79	8.32	1.94	90.84	82.03
		Cl 2 Tail	2.09	0.53	0.35	1.38	3.52	10.88	6.82	1.63	92.22	85.55
		Cl 1 Tail	6.00	0.24	0.126	1.79	3.66	16.88	4.48	1.10	94.01	89.21
		R Tail	83.12	0.058	0.027	5.99	10.79	100.00	0.80	0.21	100.00	100.00
3	100	Cl 4 Conc	9.59	7.98	1.95	93.46	79.50	9.59	7.98	1.95	93.46	79.50
		Cl 4 Tail	0.40	0.61	0.55	0.29	0.94	9.99	7.69	1.89	93.75	80.44
		Cl 3 Tail	1.21	0.42	0.33	0.62	1.70	11.20	6.90	1.73	94.37	82.14
		Cl 2 Tail	2.15	0.23	0.20	0.61	1.83	13.35	5.83	1.48	94.98	83.97
		Cl 1 Tail	7.13	0.13	0.105	1.14	3.19	20.48	3.84	1.00	96.12	87.16
		R Tail	79.52	0.04	0.038	3.88	12.84	100.00	0.82	0.24	100.00	100.00
4	200	Cl 4 Conc	7.42	10.00	2.40	93.22	75.24	7.42	10.00	2.40	93.22	75.24
		Cl 4 Tail	0.42	0.82	0.83	0.43	1.48	7.84	9.51	2.32	93.65	76.72
		Cl 3 Tail	1.10	0.50	0.51	0.69	2.37	8.94	8.40	2.09	94.34	79.09
		Cl 2 Tail	2.40	0.30	0.34	0.91	3.46	11.34	6.69	1.72	95.25	82.55
		Cl 1 Tail	9.79	0.112	0.100	1.38	4.14	21.13	3.64	0.97	96.63	86.69
		R Tail	78.87	0.034	0.040	3.37	13.31	100.00	0.80	0.24	100.00	100.00
5	Rghr 65	Regr Cl 4 C	3.80	18.38	3.65	85.26	60.91	3.80	18.38	3.65	85.26	60.91
	Regr 270	Regr Cl 4 T	0.25	1.38	2.40	0.43	2.64	4.05	17.33	3.57	85.69	63.55
		Regr Cl 3 T	0.45	1.06	1.60	0.59	3.16	4.50	15.70	3.38	86.28	66.71
		Regr Cl 2 T	1.37	0.87	1.18	1.45	7.11	5.87	12.24	2.86	87.73	73.82
		Regr Cl 1 T	5.42	0.66	0.32	4.37	7.60	11.29	6.68	1.64	92.10	81.42
		Cl Tail	7.51	0.30	0.12	2.75	3.95	18.80	4.13	1.03	94.85	85.37
		R Tail	81.20	0.052	0.041	5.15	14.63	100.00	0.82	0.23	100.00	100.00

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 97.64%, 90.81%, and 90.65%, respectively, at 200 mesh (one-stage grind flotation), and were 94.63%, 86.36%, and 90.24%, respectively, at 65 mesh (two-stage grind flotation). The flotation concentrate could not be upgraded beyond 9 percent copper in the one-stage grind flotation even after four cleaning. In the two-stage grind flotation the concentrate was upgraded to 13.14 percent copper and 2.58 percent nickel after one cleaning following regrinding. The sum of the copper, nickel, cobalt, iron, and sulfur contents may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The fourth cleaner concentrate (Cl 4 Conc) in the one-stage grind flotation would then have 12.5 percent gangue and the reground first cleaner concentrate (Regr Cl 1 Conc) in the two-stage grind flotation would have 11.7 percent gangue. These values of the gangue contents are appreciably lower than those of AX9002 or IP9002, yet the grades of copper in flotation concentrates, particularly in the one-stage grind flotation, were surprisingly low. Such an observation would indicate that this sample contained a large amount of iron sulfides. In fact, the iron and sulfur contents of Cl 4 Conc are seen to be very high. Even though a high copper grade of 19.98 percent was attained in the fourth cleaner concentrate

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON DP9002

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 7 Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 30°C Rougher pH: 8.7							
Cl 4 Conc	8.60	8.94	2.32	0.18	44.38	31.71	0.13
Cl 4 Tail	0.43	0.82	0.98	0.078	32.13	15.59	-
Cl 3 Tail	0.74	0.87	0.72	0.067	32.87	15.83	-
Cl 2 Tail	2.00	0.35	0.32	0.036	30.95	13.51	-
Cl 1 Tail	5.22	0.127	0.116	0.019	20.04	6.85	-
R Tail	83.01	0.023	0.027	0.012	12.30	0.44	-
Flotation Feed	100.00	0.82	0.215	0.025	15.96	3.84	0.085
Test No. 8 Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 28°C Rougher pH: 8.3							
Regr Cl 4 Conc	3.50	19.98	3.21	0.26	38.81	34.26	0.076
Regr Cl 4 Tail	0.10	2.05	5.30	0.44	44.90	30.18	-
Regr Cl 3 Tail	0.50	1.22	2.25	0.20	45.66	28.76	-
Regr Cl 2 Tail	1.35	0.62	0.86	0.07	42.57	25.29	-
Regr Cl 1 Tail	5.98	0.32	0.37	0.037	39.71	22.21	-
Cl Tail	7.50	0.31	0.16	0.015	23.56	9.35	-
R Tail	81.07	0.053	0.034	0.015	12.11	0.50	-
Flotation Feed	100.00	0.89	0.215	0.025	15.25	3.92	-

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON DP9002

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 7 One-stage Grind Flotation																	
Cleaner 4	8.60	8.94	2.32	0.180	44.38	31.71	94.75	81.80	55.36	23.75	69.85	91.40	0.047	0.049	0.014	13.41	1.29
Cleaner 3	9.03	8.55	2.26	0.175	43.85	30.94	95.18	83.52	56.43	24.62	71.57	90.97	0.043	0.044	0.013	13.32	1.22
Cleaner 2	9.77	7.97	2.14	0.166	42.99	29.80	95.97	85.69	58.22	26.11	74.57	90.23	0.036	0.039	0.013	13.17	1.00
Cleaner 1	11.77	6.68	1.83	0.144	40.95	27.03	96.83	88.31	60.72	29.97	81.49	88.23	0.029	0.032	0.013	12.76	0.82
Rougher	16.99	4.66	1.30	0.106	34.55	20.83	97.64	90.81	64.29	36.50	90.65	83.01	0.023	0.027	0.012	12.30	0.44
Test No. 8 Two-stage Grind Flotation																	
Regr Cleaner 4	3.50	19.98	3.21	0.260	38.81	34.26	87.27	55.57	33.71	8.40	28.90	96.50	0.106	0.093	0.019	15.38	3.06
Regr Cleaner 3	3.60	19.48	3.27	0.264	39.17	34.15	87.53	58.19	35.19	8.71	29.63	96.40	0.104	0.088	0.018	15.34	3.03
Regr Cleaner 2	4.10	17.26	3.14	0.256	40.24	33.49	88.29	63.78	38.89	10.19	33.10	95.90	0.098	0.076	0.017	15.17	2.90
Regr Cleaner 1	5.45	13.14	2.58	0.211	40.92	31.46	89.34	69.51	42.59	13.77	41.33	94.55	0.090	0.065	0.016	14.78	2.58
Cleaner	11.43	6.43	1.42	0.120	40.33	26.62	91.72	80.43	50.74	28.46	73.34	88.57	0.075	0.045	0.015	13.09	1.25
Rougher	18.93	4.01	0.92	0.078	33.70	19.78	94.63	86.36	54.81	39.39	90.24	81.07	0.053	0.034	0.015	12.11	0.50

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF DP9002

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 7 - One-stage Grind Flotation (Minus 200 mesh)		
+150	1.02	-	4.07
+200	4.55	0.66	10.60
+270	21.53	8.34	27.59
+400	18.78	14.47	13.48
-400	54.12	76.53	44.26
	(b) Test 8 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	0.17	-	1.64
+65	5.61	-	9.42
+100	18.41	-	20.70
+150	27.00	-	28.30
+200	14.09	-	10.55
+270	5.73	1.84	6.82
+400	7.31	10.37	4.99
-400	21.68	87.79	17.58

*Cl 4 Conc and Regr Cl 4 Conc, respectively

after regrinding (Regr Cl 4 Conc), the Regr Cl Tails are seen to be high in iron and sulfur indicating that iron sulfides were rejected more or less preferentially after regrinding. Somewhat higher sulfur contents of R Tails, 0.44 percent and 0.50 percent, respectively, are also in agreement with a well-known view that pyrrhotite is less floatable than copper sulfides.

Since some magnetic particles were observed with a hand magnet to be present in the concentrates, Davis magnetic tube tests were performed on a one-stage flotation concentrate to investigate if the flotation concentrate might be upgraded in copper. The results are shown in Table 7. Approximately 5 percent by weight of the concentrate was found to be magnetic, low in copper, high in iron, and high in sulfur. It was surmised that the magnetic fraction consisted of monoclinic, or magnetic, pyrrhotite. This observation indicates that the DP9002 sample is quite different from the AX9002 and IP9002 samples in which pyrrhotite of magnetic variety was much less. Nevertheless, the concentrate grade of the DP9002 sample could not be improved by magnetic separation beyond 11 percent copper.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, and R Tail samples in the one-stage grind flotation test and the Feed, Regr Cl 4 Conc, Cl Tail, and R Tail samples in the two-stage grind flotation tests were analyzed by Barringer Research Ltd. The results are given in Tables 8 and 9. In these tables it is seen that the concentration of such trace elements as zinc and silver notably increased. The amount of mercury in the cleaner concentrate increased to some extent. These increases are apparently due to the close association of these elements with sulfide minerals. The copper, nickel, iron and cobalt analyses by

TABLE 7. DAVIS MAGNETIC TUBE TEST RESULTS ON A MINUS 200 MESH FLOTATION CONCENTRATE OF DP9002 (TEST 6)

Product	% Wt	% Cu	% Ni	% Fe	% S	% Cu Rec	% Ni Rec	% Fe Rec	% S Rec
Magnetic	5.22	2.46	1.15	56.83	33.70	1.25	2.40	7.09	5.57
Nonmagnetic	94.78	10.75	2.57	41.08	31.49	98.75	97.60	92.91	94.43
Composite	100.00	10.32	2.50	41.91	31.61	100.00	100.00	100.00	100.00

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON DP9002 (TEST 7 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	7.05		1.05				7.88	
B	0.00443		nd				0.00518	
Be	0.00008		nd				0.00009	
Ca	5.21		0.729				5.86	
Cu	0.728	0.82	8.79	8.94			0.0135	0.023
Fe	13.0	15.96	45.2	44.38			10.2	12.30
Mg	3.49		0.583				3.81	
Mn	0.1310		0.0276				0.144	
P	0.1250		0.208				0.1010	
Ba	0.0226		0.0040				0.0256	
Se	nd		nd				nd	
Te	nd		nd				nd	
As	nd		nd				nd	
Si	0.0635		0.00986				0.0887	
Sr	0.0196		0.00315				0.0222	
Zr	0.0123		0.00187				0.0126	
Ti	1.56		0.132				1.56	
V	0.0193		0.00519				0.0202	
Zn	0.0225		0.108				0.0136	
Th	nd		nd				nd	
K	0.3540		0.0400				0.3990	
Na	1.69		0.27				1.9	
Cd	nd		nd				nd	
Cr	0.037		0.00				0.0254	0.012
Co	0.0196	0.025	0.1640	0.18			0.0061	
Ag	0.0003		0.00249				0.00007	
Mo	nd		nd				nd	
Ni	0.176	0.215	2.13	2.32			0.0219	0.027
Pb	nd		nd				nd	
Mg**	0.0000070		0.0000160				0.0000070	

(Continued)

TABLE 8 - CONTINUED (DP9002)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
F^-	1***							
Cl^-	280							
NO_2^-	59							
$PO_4^{\equiv}$	<40							
Br^-	<16							
NO_3^-	64							
$SO_4^{=}$	1523							

* Conventional AA analyses
** 0.0000001% = 1 ppb
***All the anion analysis results in ppm

TABLE 9. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON DP9002 (TEST 8 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	7.25		0.223		6.18		7.93	
B	0.0117		nd		0.0118		0.0203	
Be	0.00009		nd		0.00008		0.00009	
Ca	5.35		0.144		4.19		5.9	
Cu	0.835	0.89	20.5	19.98	0.296	0.31	0.0419	0.053
Fe	13.0	15.25	43.2	38.81	17.9	23.56	10.3	12.11
Mg	3.44		0.128		2.83		3.83	
Mn	0.128		0.00807		0.103		0.143	
P	0.122		0.389		0.111		0.098	
Ba	0.0255		0.0021		0.0225		0.0326	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
As	nd		0.0020		nd		nd	
Si	0.113		0.0148		0.0762		0.21	
Sr	0.0205		0.0006		0.0177		0.0223	
Zr	0.0121		0.00102		0.0109		0.0128	
Ti	1.57		0.0419		1.07		1.57	
V	0.0186		0.00155		0.0178		0.0213	
Zn	0.0220		0.217		0.017		0.0149	
Th	nd		nd		0.00016		nd	
K	0.354		0.009		0.343		0.387	
Na	1.75		0.04		1.49		1.93	
Cd	nd		nd		nd		nd	
Cr	0.0184		nd		0.0495		0.0151	
Co	0.0204	0.025	0.232	0.26	0.0138	0.015	0.0063	0.015
Ag	0.00028		0.0041		0.00036		0.00009	
Mo	nd		nd		nd		nd	
Ni	0.1810	0.215	3.25	3.21	0.122	0.16	0.0182	0.034
Pb	nd		nd		nd		nd	

*Conventional AA analyses

Barringer and by the MRRC are seen to be in reasonably good agreement. The silicon analyses in Tables 8 and 9 appear to be unreasonably low since the feed and tailing samples were essentailly silicates.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were analyzed in a similar manner after one week and one month of standing. The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 10 shows the amounts of residual flotation reagents in the liquors. Tables 11 and 12 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease from near 9 during flotation to about 8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed appreciably in one week, and these reagents became virtually absent after one month. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors upon aging. Of particular interest is the fact that the concentration of copper remained near 10 ppb throughout the period. In fact, these values were lower than those in the distilled water used at the time. The decrease in the presence of the ore sample may be interpreted to be due to adsorption and that upon the addition of flotation reagents to the precipitation of insoluble copper xanthate.

TABLE 10. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTIONS OF DP9002

Sampling Time	One-stage Grind Flotation (Test 7)			Two-stage Grind Flotation (Test 8)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	8.7	0.74	5.99	8.2	0.76	6.73
After 1 Day	8.2	0.66	3.86	8.0	0.53	4.20
After 1 Week	8.1	0.30	0.00	8.0	0.15	0.00
After 1 Month	7.8	0.25	0.00	7.8	0.12	0.00

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF DP9002 (TEST 7 - MINUS 200 MESH GRIND)

	Distilled Water (8-4-77)	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al	nd	0.42	0.32	0.23	0.22	0.14
B	nd	0.020	0.016	0.014	0.009	0.014
Ba	nd	nd	nd	nd	nd	nd
Be	nd	nd	nd	nd	nd	nd
Ca	nd	17.0	11.0	14.3	19.1	25.9
Cu	0.068	0.017	0.007	0.007	0.009	0.008
Fe	nd	0.175	0.069	0.010	0.107	0.016
K	nd	nd	1	1	5.9	7.0
Mg	nd	14.9	9.24	10.6	10.4	11.5
Mn	0.0059	0.0027	nd	nd	0.0229	0.0246
Na	nd	14.0	8	8	7	7
P	nd	nd	nd	nd	nd	nd
Se	nd	nd	nd	nd	nd	nd
Te	nd	nd	nd	nd	nd	nd
Pb	nd	nd	nd	nd	nd	nd
Si	nd	2.31	2.61	2.44	3.74	4.66
Sr	0.0002	0.0272	0.0162	0.0174	0.0195	0.026
Ti	nd	0.007	0.003	nd	0.002	nd
V	nd	0.004	0.002	0.003	0.007	0.005
Zn	nd	nd	0.58	0.14	2.11	0.27
Th	nd	nd	nd	nd	nd	nd
Ag	nd	nd	nd	nd	nd	nd
As	0.2	nd	0.2	0.2	nd	nd
Cd	nd	0.07	nd	nd	nd	nd
Co	nd	nd	nd	nd	nd	nd
Cr	nd	0.025	0.015	0.020	0.034	0.017
Mo	nd	0.20	0.20	0.16	0.25	0.34
Ni	nd	0.11	nd	nd	nd	nd
Zr	nd	nd	nd	nd	nd	nd

TABLE 12. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF DP9002 (TEST 8 - MINUS 65 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		0.43	0.31	0.24	0.20	0.09
B		0.020	0.009	0.13	0.008	0.031
Ba		nd	nd	nd	nd	nd
Be		nd	nd	nd	nd	nd
Ca		18.3	13.0	16.8	26.3	32.2
Cu		0.021	0.003	0.009	0.010	nd
Fe		0.362	0.103	0.019	0.023	nd
K		6.2	7.3	8.0	6.0	7
Mg		11.1	8.02	9.73	12.1	13.3
Mn		0.0246	0.007	0.0158	0.0387	0.0194
Na		7	5	5	6	3
P		nd	nd	nd	nd	nd
Se		nd	5	nd	nd	nd
Te		nd	nd	nd	nd	nd
Pb		nd	nd	nd	nd	nd
Si		1.91	1.88	2.28	4.17	6.03
Sr		0.026	0.0166	0.0188	0.026	0.0291
Ti		0.022	0.004	nd	nd	nd
V		0.010	0.005	0.005	0.007	0.009
Zn		0.14	0.05	nd	0.05	nd
Th		nd	nd	nd	nd	nd
Ag		nd	nd	nd	nd	nd
As		nd	nd	nd	nd	nd
Cd		nd	nd	nd	nd	nd
Co		nd	nd	nd	nd	nd
Cr		0.029	0.20	0.025	0.031	0.050
Mo		0.17	0.22	0.17	0.17	nd
Ni		nd	nd	nd	nd	nd
Zr		nd	nd	nd	nd	nd

The concentrations of nickel ions in the pulp solutions remained essentially below the limit of detection by the analytical method used (90 ppb). Of note is the zinc-ion concentration which remained at a few tenths of one ppm and on one occassion 2 ppm. Perhaps the zinc ions might have been released by the exchange reaction with copper and nickel ions.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of Table 6. The size distributions of concentrates in the same range were determined by microscreening (Table 13). The data in the 'subsieve' range are of particular interest since the air-borne dusts are said to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200 mesh grind would have about 4 percent by weight of minus 5-μm particles. At a 65-mesh grind, however, minus 5-μm particles would be about 2 percent. The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

TABLE 13. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF DP9002

Size, μm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 7 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	28.47	-
+20	87.31	38.29	86.47
+10	5.16	18.59	6.68
+5	3.10	14.65**	2.94
-5	4.43	-	3.91
	(b) Test 8 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	1.03	-
+20	93.22	20.96	94.50
+10	2.94	22.30	2.01
+5	1.54	55.71**	1.41
-5	2.30	-	2.08

* Cl 4 Conc and Regr Cl 4 Conc, respectively
**Minus 10 μm

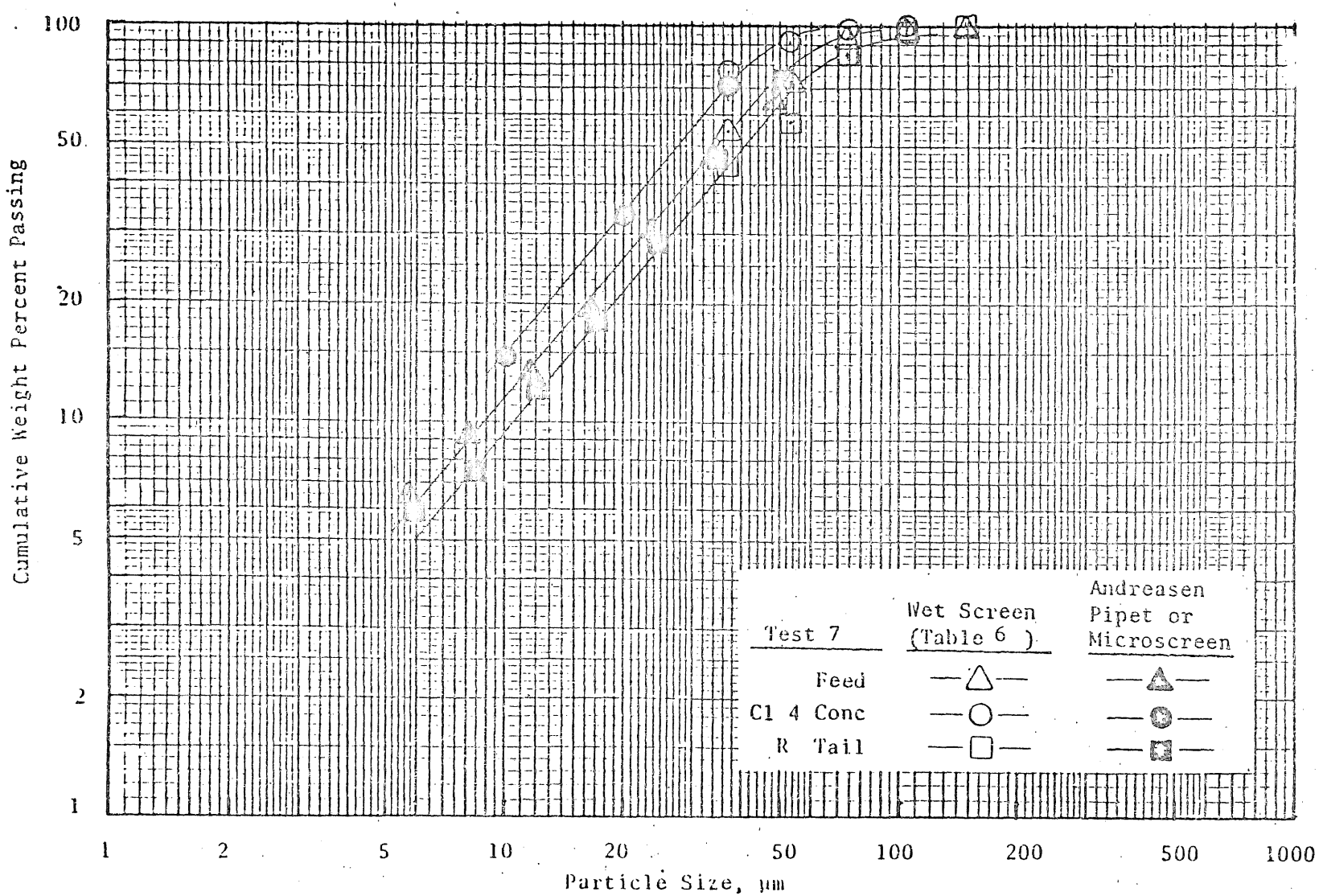


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF DP9002 (MINUS 200 MESH GRIND)

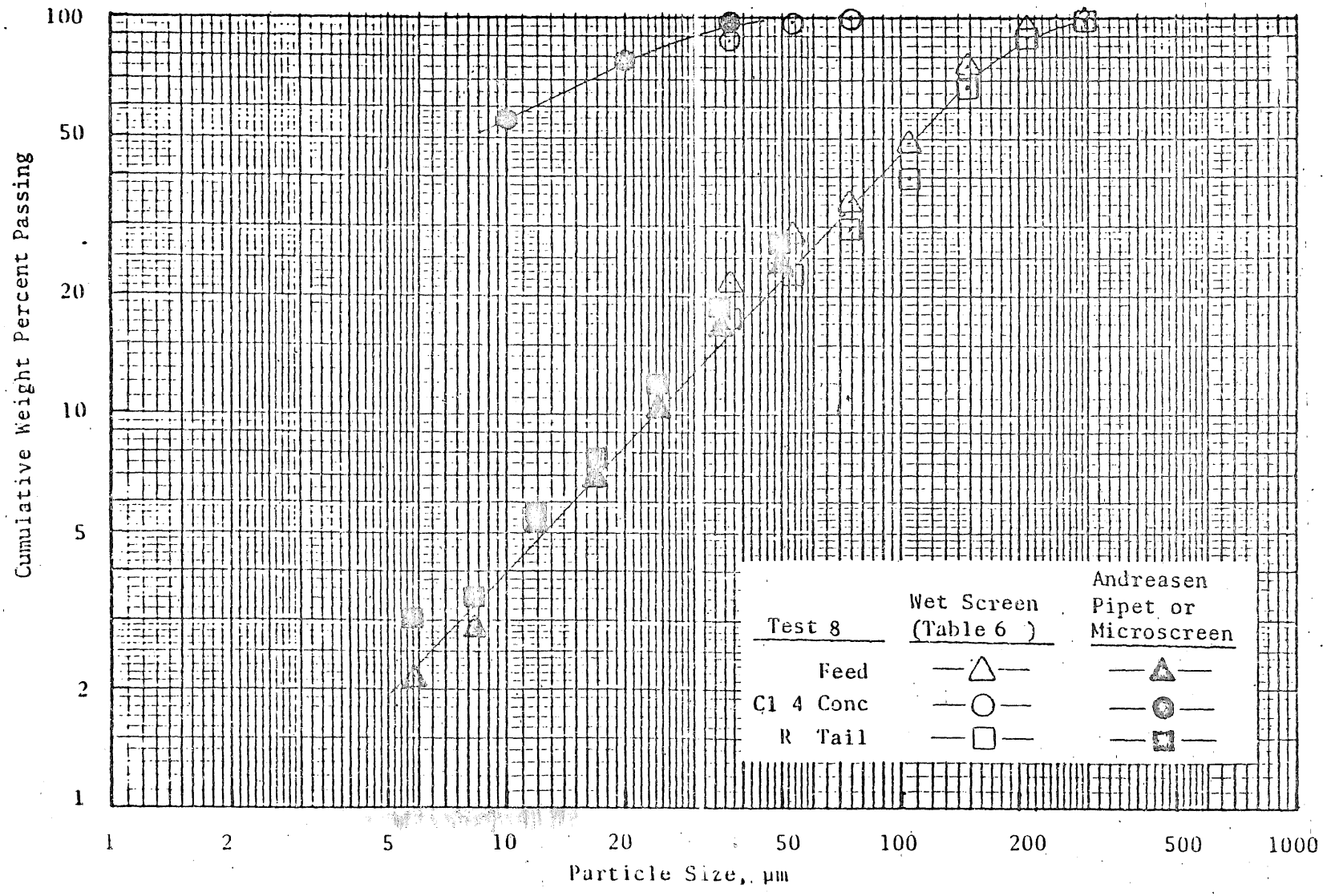


FIGURE 4. SIZE DISTRIUBITONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF DP9002
(MINUS 65 MESH FOR FEED AND TAILING, MINUS 270 MESH FOR CONCENTRATE)

To investigate how various elements are distributed over different size fractions in the 'subsieve' range the feed and the rougher tailing samples were separated into +20, 20/10, 10/5 and -5 μm fractions by the sedimentation sizing method, and the size distributions of the concentrates were determined by microscreening to 10 μm. Each size fraction of the feed, concentrate and rougher tailing was analyzed by Barringer Research Ltd. and the results are given in Table 14. In the rougher tailing of this sample heavy metals are seen to be, more or less, evenly distributed over all the sizes. The copper, nickel and zinc contents in the minus 5-μm fraction in the rougher tailing are only somewhat higher than the other fractions. It is also noted in the table that small amounts of arsenic, cadmium, molybdenum and lead were present in the smaller size fractions of the flotation concentrate although these elements were reported to be below the detection limits in the concentrate as a whole in Table 8.

Modified Flotation Test Results

In the preliminary series of flotation tests showing the effect of mesh-of-grind (Table 4) it was felt that the standard flotation procedures would recover all the recoverable sulfides judging from the copper and nickel analyses of rougher tailings. Hence, the standardized flotation tests were performed and the flotation products were analyzed for five elements, namely copper, nickel, cobalt, iron and sulfur. Their rougher tailings in Table 5, however, analyzed 0.44 and 0.50 percent sulfur, respectively, for the one-stage grind and the two-stage grind flotation tests. Since the rougher tailings of all the samples tested except for DP9002 and AX9004 Samples analyzed in the neighborhood of 0.1 percent sulfur, the above values of 0.44 and 0.50 percent

TABLE 14. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT ON SIZE FRACTIONS OF FLOTATION PRODUCTS OF DP9002 (TEST 7 - ONE-STAGE GRIND FLOTATION)

	Feed				Concentrate				Rougher Tailing			
	+20 μm	20/10 μm	10/5 μm	-5 μm	+37 μm	37/20 μm	20/10 μm	-10 μm	+20 μm	20/10 μm	10/5 μm	-5 μm
Al	8.33	9.49	9.0	9.09	1.88	0.719	0.471	0.435	8.91	10.8	10.2	9.21
B	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Be	0.00013	0.00012	0.00011	0.00012	nd	nd	nd	nd	0.00013	0.00014	0.00013	0.00012
Ca	6.1	6.24	5.84	5.91	1.08	0.477	0.372	0.313	6.32	6.73	6.26	5.66
Cu	0.77	1.29	1.61	1.04	7.64	9.86	11.9	18.2	0.0661	0.0313	0.0801	0.0918
Fe	16.1	14.1	14.9	13.7	36.0	37.2	36.8	32.8	12.1	9.64	10.2	11.4
Mg	3.88	3.2	3.2	3.4	0.86	0.455	0.424	0.453	3.91	3.24	3.11	3.27
Mn	0.156	0.126	0.13	0.14	0.0327	0.0187	0.0179	0.0282	0.161	0.124	0.124	0.132
P	0.062	nd	nd	nd	nd	nd	nd	nd	0.081	0.11	0.096	0.097
Ba	0.0117	0.0159	0.0153	0.0167	0.0038	0.0057	0.005	0.005	0.163	0.229	0.191	0.164
Se												
Te												
As	nd	nd	nd	nd	nd	0.002	0.002	0.002	nd	nd	nd	nd
Si	2.18	2.53	2.36	2.57	0.813	0.294	0.429	0.657	2.19	3.21	2.54	2.08
Sr	0.0238	0.0291	0.0263	0.0273	0.00598	0.00237	0.00141	0.00181	0.0271	0.0332	0.033	0.0268
Zr	0.0183	0.0194	0.016	0.0128	0.00317	0.00196	0.00232	0.00262	0.0185	0.0217	0.0177	0.0123
Ti	1.62	1.46	1.59	1.45	0.16	0.0786	0.0768	0.121	1.69	1.38	1.46	1.4
V	0.0252	0.0176	0.0168	0.0156	0.00943	0.00764	0.00805	0.0112	0.0252	0.0172	0.0164	0.0157
Zn	0.019	0.0199	0.023	0.0266	0.0325	0.0396	0.0527	0.116	0.0154	0.0133	0.0132	0.0185
Th	0.00076	0.00092	0.00092	0.0009	0.0009	nd	nd	nd	0.00046	0.00097	0.00064	0.00081
K	0.794	0.763	0.728	0.917	0.06	nd	nd	nd	0.888	0.966	0.985	1.1
Na	2.37	2.72	2.58	2.54	0.6	0.25	0.17	0.16	2.47	3.06	2.79	2.37
Cd	nd	nd	nd	nd	nd	nd	nd	0.0011	nd	nd	nd	nd
Cr	0.0387	0.0773	0.0681	0.0548	nd	nd	0.00574	0.186	0.0214	0.0606	0.066	0.0683
Co	0.0223	0.0231	0.0198	0.0206	0.111	0.165	0.194	0.173	0.0067	0.0053	0.0057	0.0079
Ag	0.00044	0.00062	0.00078	0.0007	0.00211	0.00266	0.00337	0.0052	0.00011	0.00009	0.00007	0.00012
Mo	nd	0.0015	0.0017	0.0014	nd	nd	nd	0.0054	nd	0.0015	nd	nd
Ni	0.2	0.225	0.178	0.187	1.24	1.88	2.42	1.9	0.0252	0.0346	0.0413	0.0602
Pb	nd	nd	nd	nd	nd	nd	0.0045	0.034	nd	nd	nd	nd

were thought to be unexpectedly high. In an attempt to recover the remaining sulfides in the rougher tailings, the effect of the stage addition of the collector was tested. For this purpose the modified flotation test procedures developed for AX9004 Sample, shown in Figures 5 and 6, were used. In the present tests, however, the levels of the collector additions were lower than those for AX9004 Sample since the amounts of remaining sulfides in the rougher tailings were less. The flotation results are given in Table 15, and those in the scavenger circuits are summarized in Table 16.

TABLE 16. SUMMARY OF FLOTATION RESULTS IN SCAVENGER CIRCUITS OF TESTS 14 AND 15

Test No.		Product	% Wt	% Cu	% Ni	% S
14	One-stage Grind Flotation	Sc 2 Tail	56.93	0.019	0.027	0.028
		Sc 1 Tail	63.59	0.020	0.027	0.050
15	Two-stage Grind Flotation	Sc 2 Tail	72.08	0.069	0.026	0.090
		Sc 1 Tail	76.13	0.073	0.027	0.14

It is readily apparent that the sulfur contents in the tailings in the present samples could be lowered to less than 0.1 percent with additional stages of the collector addition. It is surprising that the copper contents in the tailings could be lowered to 0.02 percent as compared to the normal 0.05 percent that was obtained in many other samples. The nickel contents remained constant at 0.027 percent regardless of the number of scavenger stages indicating that the size of liberation of recoverable nickel-bearing sulfides is coarser than that of copper-bearing sulfides.

In Table 15 the copper contents of concentrates are seen to be lower than those in Table 5 which would indicate that additional pyrrhotite was recovered thereby diluting the concentrates. Apparently, the regrinding of

TABLE 15(a). MODIFIED FLOTATION TEST RESULTS ON DP9002

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 14 Grind: -200 mesh Flotation Time: Rougher and Scavenger 10 min, Cleaner 5 min							
Cl 4 Conc	10.46	6.89	1.59	0.190	46.80	29.96	0.036
Cl 4 Tail	0.84	0.30	0.43	0.048	21.25	6.79	
Cl 3 Tail	1.59	0.22	0.28	0.032	18.18	4.86	
Cl 2 Tail	5.40	0.106	0.138	0.021	15.23	3.07	
Cl 1 Tail	18.12	0.040	0.067	0.015	11.70	0.81	
Sc 2 Conc	6.66	0.027	0.030	0.014	10.38	0.24	
Sc 2 Tail	56.93	0.019	0.027	0.016	11.03	0.028	
Test No. 15 Grind: Rougher - 65 mesh Regr Cleaner -270 mesh Flotation Time: Rougher and Scavenger 10 min, Cleaner 5 min							
Regr Cl 4 Conc	6.93	9.96	2.14	0.23	47.60	35.01	0.038
Regr Cl 4 Tail	0.33	0.48	0.89	0.097	34.18	17.83	
Regr Cl 3 Tail	0.83	0.21	0.50	0.058	36.22	18.45	
Regr Cl 2 Tail	1.77	0.136	0.26	0.034	25.81	10.47	
Regr Cl 1 Tail	5.21	0.079	0.127	0.022	21.55	8.59	
Cl Tail	8.80	0.168	0.081	0.019	13.86	2.57	
Sc 2 Conc	4.05	0.139	0.055	0.015	11.15	0.99	
Sc 2 Tail	72.08	0.069	0.026	0.016	11.28	0.090	

TABLE 15(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF MODIFIED FLOTATION TESTS ON DP9002

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 14 One-stage Grind Flotation																	
Cleaner 4	10.46	6.89	1.59	0.190	46.80	29.96	95.80	78.67	57.31	32.05	86.75	89.54	0.035	0.051	0.016	11.59	0.535
Cleaner 3	11.30	6.40	1.50	0.183	44.90	28.24	96.13	80.37	58.46	33.22	88.33	88.70	0.033	0.047	0.016	11.50	0.476
Cleaner 2	12.89	5.64	1.35	0.161	41.61	25.35	96.60	82.50	59.93	35.11	90.47	87.11	0.029	0.043	0.016	11.38	0.396
Cleaner 1	18.29	4.00	0.995	0.120	33.82	18.78	97.36	86.05	63.19	40.49	95.06	81.71	0.024	0.036	0.016	11.13	0.219
Rougher + Scav 1	36.41	2.03	0.533	0.068	22.81	9.83	98.32	91.77	71.04	54.37	99.12	63.59	0.020	0.027	0.016	10.96	0.050
Test No. 15 Two-stage Grind Flotation																	
Regr Cleaner 4	6.93	9.96	2.14	0.23	47.60	35.01	89.63	76.21	49.11	21.85	67.35	93.07	0.086	0.050	0.018	12.67	1.264
Regr Cleaner 3	7.26	9.53	2.08	0.224	47.00	34.23	89.84	77.70	50.10	22.60	68.99	92.74	0.084	0.047	0.017	12.59	1.204
Regr Cleaner 2	8.09	8.57	1.92	0.207	45.90	32.61	90.06	79.86	51.58	24.59	73.24	91.91	0.083	0.043	0.017	12.38	1.049
Regr Cleaner 1	9.86	7.06	1.62	0.176	42.29	28.63	90.37	82.22	53.43	27.62	78.38	90.14	0.082	0.038	0.017	12.12	0.864
Cleaner	15.07	4.65	1.11	0.123	35.12	21.71	90.90	85.61	56.97	35.06	90.82	84.93	0.082	0.033	0.016	11.53	0.390
Rougher + Scav 1	23.87	3.00	0.728	0.085	27.29	14.65	92.82	89.26	62.11	43.14	97.09	76.13	0.073	0.028	0.016	11.27	0.138

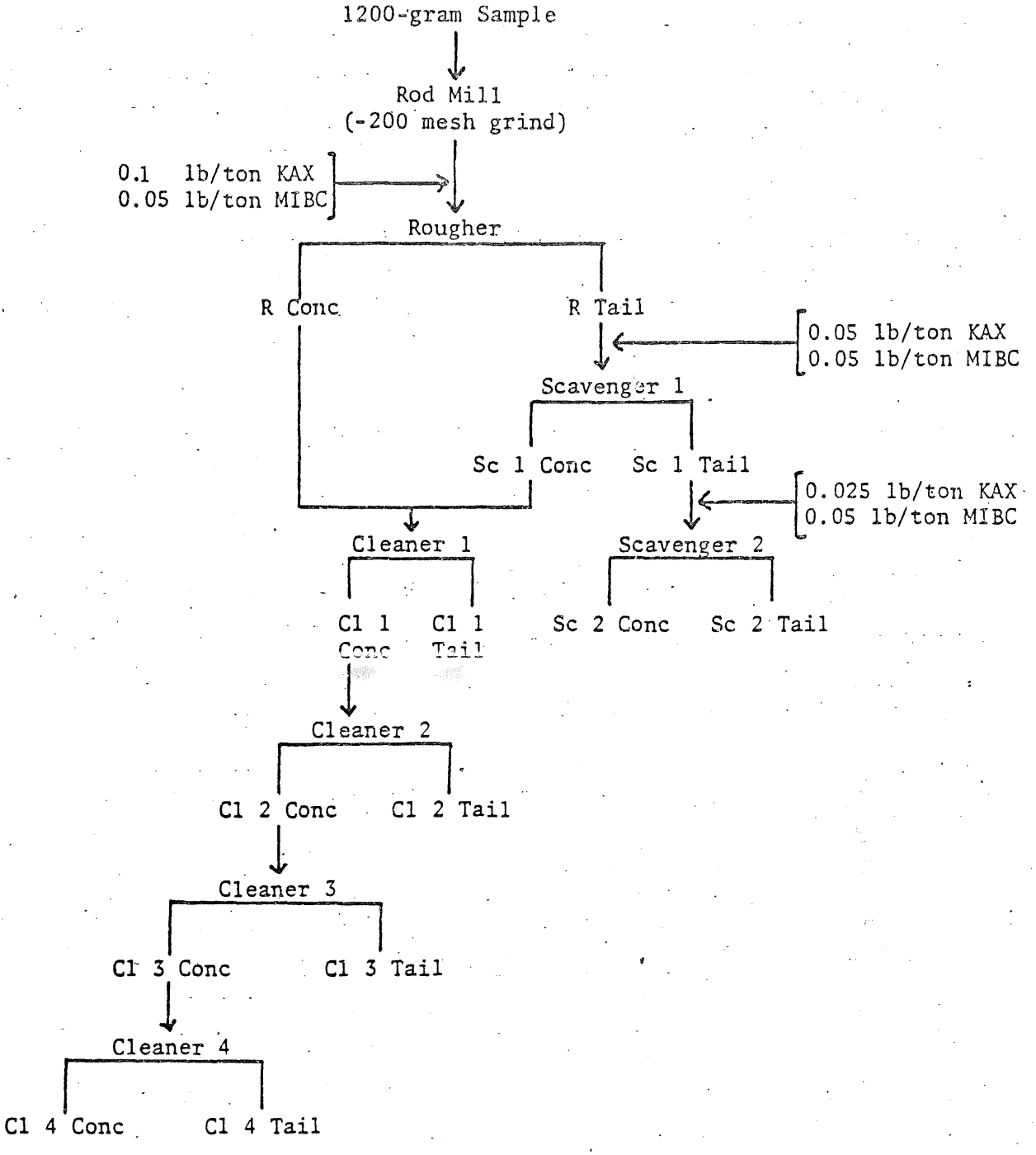


FIGURE 5. MODIFIED FLOTATION FLOWSHEET OF TEST 14 FOR DP9002

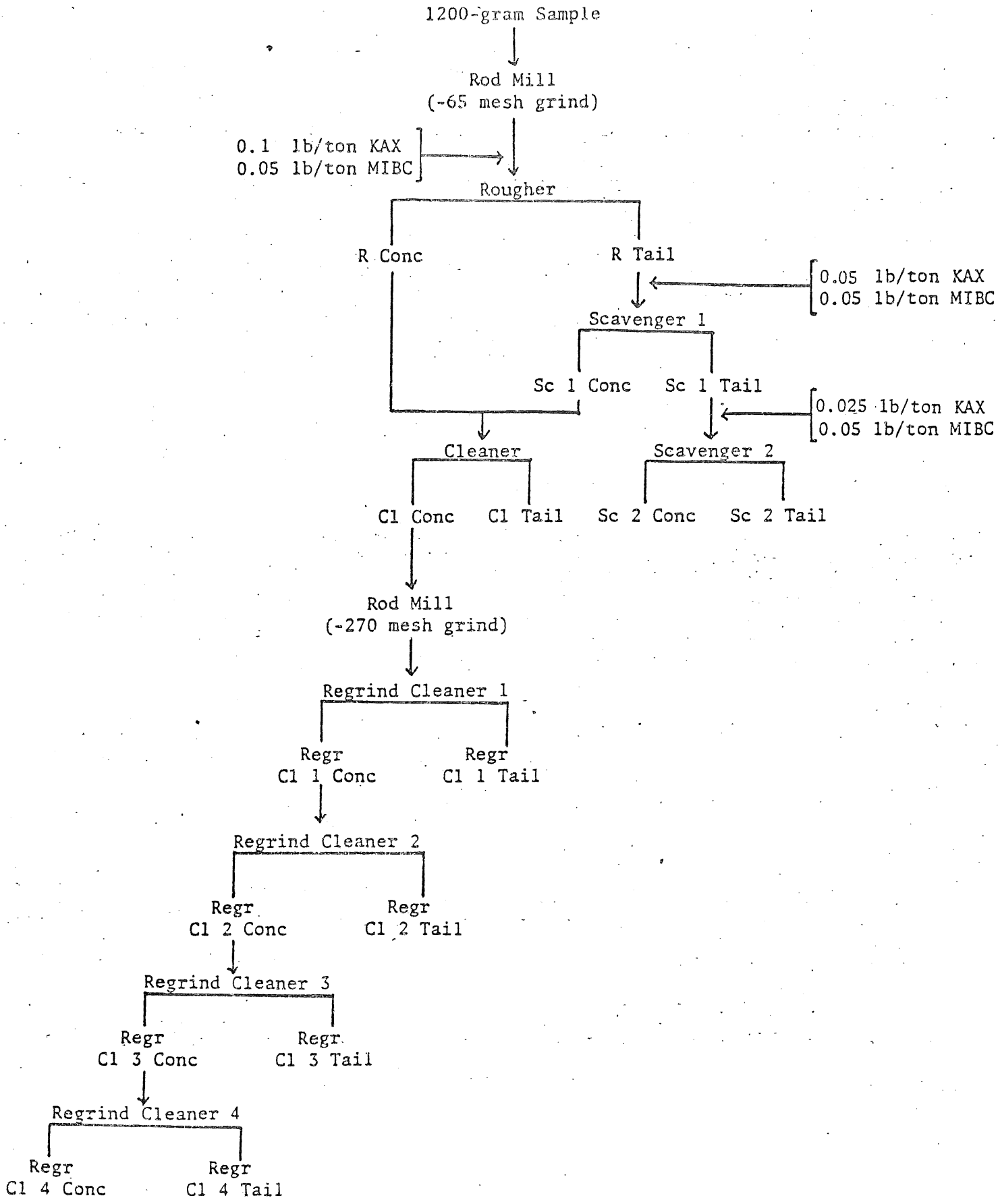


FIGURE 6. MODIFIED FLOTATION FLOWSHEET OF TEST 15 FOR DP9002

the concentrate made pyrrhotite particles less floatable and the grade of the final concentrate was higher in copper and nickel than in the one-stage grind flotation. The results of the modified flotation procedures clearly indicated that the recovery of sulfide minerals, particularly pyrrhotite, could be maximized through the stage addition of the collector, but the concentrate grade became less than 10 percent copper. It then appears that differential flotation must be considered if the concentrate grade is to be maintained above 10 percent copper. The disposal of the pyrrhotite rejected in the differential flotation step would then have to be considered.

3.4 FLOTATION TESTS ON US9001 SAMPLE

Sample Description

A U.S. Steel mineralized gabbro sample, labeled US9001, weighing approximately 122 kilograms, was received on April 30, 1977 from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. The sample was reported to have been collected from a pile of broken rock at the U.S. Steel Research Center in Coleraine. The rocks were outside and were well oxidized on the outside, and only one side of the pile had been uncovered of snow and loosened by a front-end loader. The pile contained much unmineralized rock from the Duluth Complex and other formations. The sample was collected by selecting only those pieces which contained sulfides, with each piece being individually examined. These samples, therefore, represent the best of the material available.

The whole sample was stage-crushed to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF US9001 SAMPLE

Constituent	Percent
Copper (Cu)	0.40
Nickel (Ni)	0.127
Cobalt (Co)	0.018
Iron (Fe)	10.05
Sulfur (S)	1.21
Titanium dioxide (TiO_2)	1.69
Graphite carbon (C)	0.028

Grinding Characteristics

The grinding characteristics of the US9001 sample were investigated by grinding 1200-gram batches of minus 10-mesh feed in a stainless steel laboratory rod mill at 50 percent solids for various periods of time. The size distributions of the minus 10-mesh feed and of a sample ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. The size distribution data of the ground batches are seen to be represented by straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.82. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 2. SCREEN ANALYSIS OF US9001 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 Mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	0.5	100.0	-	-	-	-	-	-	-	-
+14	16.4	99.5	-	-	-	-	-	-	-	-
+20	9.5	83.1	-	-	-	-	-	-	-	-
+28	21.0	73.6	-	-	-	-	-	-	-	-
+35	11.1	52.6	-	-	-	-	-	-	-	-
+48	8.3	41.5	4.2	100.0	-	-	-	-	-	-
+65	6.4	33.2	14.9	95.8	8.8	100.0	-	-	-	-
+100	6.0	26.8	22.2	80.9	23.1	91.2	4.0	100.0	-	-
+150	4.5	20.8	13.8	58.7	15.9	68.1	12.5	96.0	0.4	100.0
+200	4.3	16.3	11.9	44.9	13.7	52.2	22.0	83.5	3.3	99.6
+270	2.5	12.0	7.4	33.0	8.3	38.5	13.5	61.5	12.0	96.3
+325	1.6	9.5	4.2	25.6	5.0	30.2	7.8	48.0	13.6	84.3
+400	1.2	7.9	3.2	21.4	3.3	25.2	6.2	40.2	12.2	70.7
+500	2.3	6.7	6.7	18.2	7.4	21.9	15.2	34.0	23.2	58.5
-500	4.4	4.4	11.5	11.5	14.5	14.5	18.8	18.8	35.3	35.3

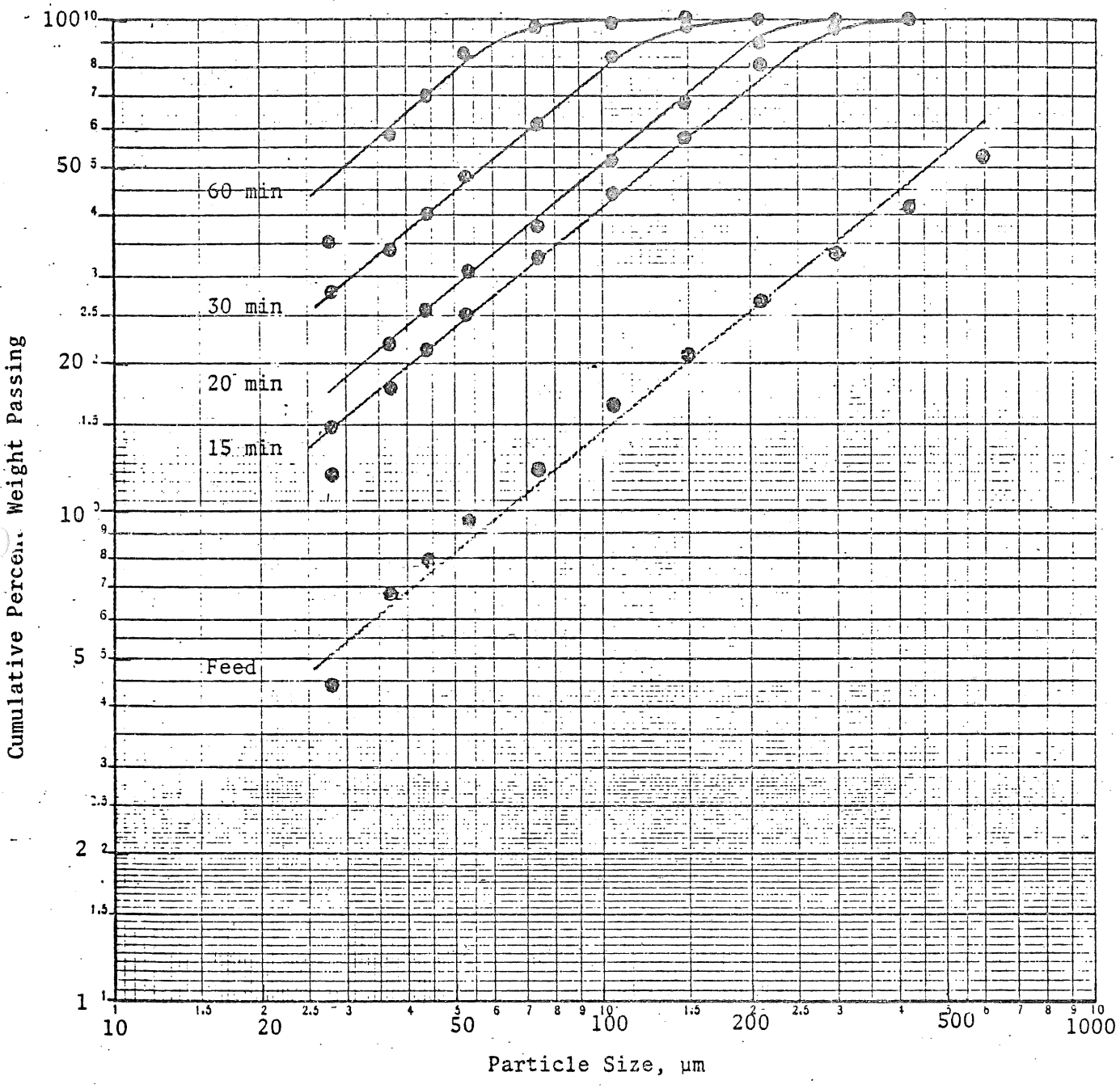


FIGURE 1. SIZE DISTRIBUTIONS OF US9001 SAMPLE AS A FUNCTION OF GRINDING TIME

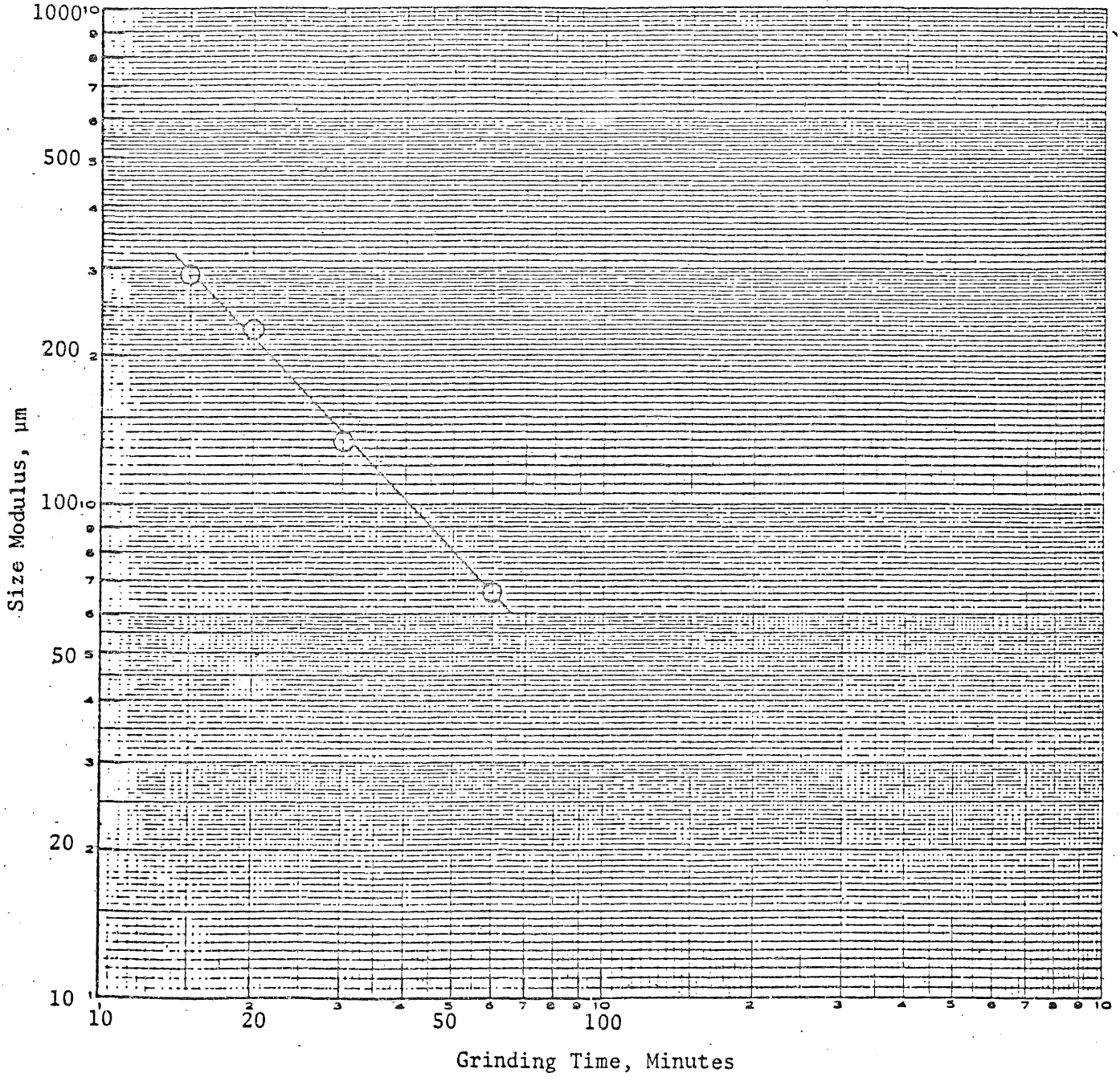


FIGURE 2. SIZE MODULI OF US9001 SAMPLE AS A FUNCTION OF GRINDING TIME

TABLE 3. BATCH GRINDING CHARACTERISTICS OF US9001 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50% SOLIDS)

Nominal Mesh-of-Grind	Grind Time Minutes	Size Modulus k, μm	80% passing μm
-10 mesh	0	-	1000
-48 mesh	15	290	225
-65 mesh	20	225	173
-100 mesh	30	133	101
-200 mesh	60	66	52

Preliminary Flotation Tests

The effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh, and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed also at 3 minutes. The results of these flotation tests are given in Table 4.

It is apparent in Table 4 that both the losses of copper and of nickel to the R Tails reached plateaus at about 8 percent and 35 percent, respectively, for minus 100- and 200-mesh grind samples. The loss of copper to R Tails tended to increase somewhat at 65 mesh (see Test 5) and noticeably at 48 mesh. It is also noted that the concentrates even after four cleaner stages analyzed about 10 percent copper and 3 percent nickel. In the two-stage grind flotation

TABLE 4. EFFECT OF MESH-OF-GRIND ON US9001

Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Cleaner - MIBC 0.06 lb/ton

Flotation Time:

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	2.99	10.00	1.86	82.14	46.28	2.99	10.00	1.86	82.14	46.28
		Cl 4 Tail + Cl 3 Tail	0.21	0.90	0.87	0.55	1.65	3.20	9.41	1.81	82.69	47.93
		Cl 2 Tail	0.58	0.217	0.48	0.82	2.48	3.78	8.04	1.61	83.51	50.41
		Cl 1 Tail	4.80	0.47	0.29	2.74	11.57	8.58	3.66	0.87	86.25	61.98
		R Tail	91.42	0.055	0.050	13.75	38.02	100.00	0.37	0.12	100.00	100.00
2	65	Cl 4 Conc	2.84	10.85	1.84	77.33	46.78	2.84	10.85	1.84	77.33	46.78
		Cl 4 Tail	0.08	2.00	1.17	0.40	0.81	2.92	10.61	1.82	77.73	47.59
		Cl 3 Tail	0.29	1.29	0.94	0.93	2.42	3.21	9.76	1.74	78.66	50.01
		Cl 2 Tail	1.55	1.10	0.67	4.29	9.30	4.76	6.94	1.39	82.95	59.31
		Cl 1 Tail	3.09	0.26	0.16	2.01	4.38	7.85	4.31	0.91	84.95	63.69
		R Tail	92.15	0.065	0.044	15.04	36.31	100.00	0.40	0.11	100.00	100.00
3	100	Cl 4 Conc	3.09	10.10	1.86	84.81	52.70	3.09	10.10	1.86	84.41	52.70
		Cl 4 Tail	0.17	1.91	0.54	0.89	0.82	3.26	9.67	1.79	85.30	53.52
		Cl 3 Tail	1.13	0.90	0.28	2.76	2.93	4.39	7.42	1.40	88.06	56.45
		Cl 2 Tail	1.17	0.53	0.19	1.68	2.02	5.56	5.97	1.15	89.74	58.47
		Cl 1 Tail	5.11	0.13	0.10	1.79	4.68	10.67	3.17	0.65	91.53	63.15
		R Tail	89.33	0.035	0.045	8.47	36.85	100.00	0.37	0.11	100.00	100.00
4	200	Cl 4 Conc	2.72	11.26	2.16	86.21	49.41	2.72	11.26	2.16	86.21	49.41
		Cl 4 Tail	0.17	1.73	0.86	0.82	1.26	2.89	10.70	2.07	87.03	50.67
		Cl 3 Tail	0.30	1.06	0.69	0.90	1.77	3.19	9.79	1.96	87.93	52.44
		Cl 2 Tail	1.78	0.41	0.27	2.06	4.03	4.97	6.43	1.35	89.99	56.47
		Cl 1 Tail	7.93	0.97	0.126	2.17	8.40	12.90	2.54	0.60	92.16	64.87
		R Tail	87.10	0.032	0.048	7.84	35.13	100.00	0.36	0.12	100.00	100.00

(Continued)

TABLE 4 (Continued)

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
5	R 65	Regr Cl 4 C	1.83	17.26	2.92	86.37	48.29	1.83	17.26	2.92	86.37	48.29
	Regr 270	Regr Cl 4 T	0.15	1.31	1.48	0.55	1.99	1.98	16.06	2.81	86.92	50.28
		Regr Cl 3 T	0.11	1.07	0.94	0.33	0.90	2.09	15.27	2.71	87.25	51.18
		Regr Cl 2 T	0.62	0.60	0.73	1.01	4.07	2.71	11.91	2.26	88.26	55.25
		Regr Cl 1 T	2.38	0.215	0.024	1.40	0.54	5.09	6.44	1.21	89.66	55.79
		Cl Tail	4.84	0.120	0.117	1.59	5.15	9.93	3.36	0.68	91.25	60.94
		R Tail	90.07	0.032	0.048	8.75	39.06	100.00	0.37	0.11	100.00	100.00

test, however, there was no difficulty in achieving a concentrate grade in excess of 14 percent copper after regrinding. It appears, therefore, that the two-stage grind flotation had a definite advantage over the one-stage grind flotation in achieving the grade of concentrate.

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 93.61%, 70.72% and 97.69%, respectively, at 200 mesh (one-stage grind flotation), and were 83.17%, 68.73%, and 92.19%, respectively, at 65 mesh (two-stage grind flotation). The last copper recovery figure was more in line with the results of Test 2, but apparently it could be improved to exceed 90 percent as seen in the results of Test 5. Perhaps, either the mesh-of-grind, or the level of the collector addition, might have been in the critical range. The flotation concentrate could be upgraded to 10.62 percent copper and 1.94 percent nickel in the one-stage grind flotation after four cleanings, whereas in the two-stage grind flotation the concentrate was upgraded to 13.51 percent copper and 2.37 percent nickel after two cleanings following regrinding. The sum of the copper, nickel, cobalt, iron, and sulfur contents may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The fourth cleaner concentrate (Cl 4 Conc) in the one-stage grind flotation would then have 18.6

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON US9001

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 6 Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 27°C Rougher pH: 7.8							
Cl 4 Conc	3.32	10.62	1.94	0.128	39.94	28.73	0.109
Cl 4 Tail	0.25	0.84	0.57	0.045	23.88	10.67	-
Cl 3 Tail	0.34	0.68	0.48	0.036	20.20	6.12	-
Cl 2 Tail	1.02	0.34	0.24	0.020	14.75	3.11	-
Cl 1 Tail	10.64	0.097	0.11	0.012	12.01	1.03	-
R Tail	84.43	0.03	0.04	0.010	10.28	0.032	-
Flotation Feed	100.00	0.39	0.11	0.013	11.15	1.14	0.16
Test No. 7 Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 25°C Rougher pH: 7.4							
Regr Cl 4 Conc	2.06	15.01	2.56	0.162	46.06	34.17	0.084
Regr Cl 4 Tail	0.08	1.59	1.12	0.070	37.62	20.49	-
Regr Cl 3 Tail	0.17	0.92	0.77	0.053	33.06	14.68	-
Regr Cl 2 Tail	0.61	0.52	0.43	0.039	25.55	10.25	-
Regr Cl 1 Tail	2.30	0.22	0.23	0.022	23.48	8.73	-
Cl Tail	5.28	0.21	0.115	0.019	12.75	0.92	-
R Tail	89.50	0.075	0.035	0.018	11.99	0.10	-
Flotation Feed	100.00	0.39	0.10	0.018	12.44	1.18	

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON US9001

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 6 One-stage Grind Flotation																	
Cleaner 4	3.32	10.62	1.94	0.128	39.94	28.73	89.02	55.81	29.86	11.50	81.47	96.68	0.045	0.052	0.011	10.59	0.225
Cleaner 3	3.57	9.94	1.84	0.123	38.94	27.48	89.55	57.02	30.55	12.02	83.78	96.43	0.043	0.051	0.010	10.56	0.197
Cleaner 2	3.91	9.13	1.72	0.115	37.34	25.63	90.13	58.41	31.24	12.63	85.57	96.09	0.041	0.050	0.010	10.52	0.176
Cleaner 1	4.93	7.31	1.42	0.095	32.66	20.97	91.01	60.58	32.63	13.93	88.30	95.07	0.038	0.048	0.010	10.47	0.144
Rougher	15.57	2.38	0.52	0.039	18.56	7.35	93.61	70.72	41.66	24.99	97.69	84.43	0.030	0.040	0.010	10.28	0.032
Test No. 7 Two-stage Grind Flotation																	
Regr Cleaner 4	2.06	15.01	2.56	0.162	46.06	34.17	77.57	52.65	15.48	7.23	61.38	97.94	0.091	0.048	0.018	12.45	0.452
Regr Cleaner 3	2.14	14.51	2.50	0.159	45.79	33.66	77.90	53.45	15.95	7.46	62.81	97.86	0.090	0.048	0.018	12.43	0.436
Regr Cleaner 2	2.31	13.51	2.37	0.152	45.02	32.26	78.30	54.75	16.42	7.92	64.99	97.69	0.089	0.046	0.018	12.37	0.411
Regr Cleaner 1	2.92	10.80	1.97	0.127	41.10	27.66	79.10	57.35	17.36	9.13	70.44	98.08	0.086	0.044	0.018	12.30	0.349
Cleaner	5.22	6.14	1.20	0.081	33.33	19.32	80.38	62.64	19.71	13.24	87.95	94.78	0.083	0.039	0.018	12.03	0.146
Rougher	10.50	3.16	0.655	0.050	22.95	10.07	83.17	68.73	24.41	18.34	92.19	89.50	0.075	0.035	0.018	11.99	0.100

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF US9001

Size, mesh	Feed % Wt	Concentrate % Wt	Tailing % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+150	0.71	-	0.49
+200	8.01	0.58	6.95
+270	19.53	5.83	19.38
+400	24.07	24.49	24.76
-400	47.68	69.10	48.42
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	4.23	-	1.86
+65	15.89	-	13.64
+100	19.89	-	22.22
+150	14.26	-	16.57
+200	13.13	-	16.46
+270	7.21	1.24	6.93
+400	6.53	2.02	7.30
-400	18.86	96.74	15.02

percent gangue and the reground second cleaner concentrate (Regr Cl 2 Conc) in the two-stage grind flotation would have 6.7 percent gangue. These values of the gangue contents are appreciably lower than those of most of the other Duluth gabbro samples, yet the grades of copper in flotation concentrates, particularly in the one-stage grind flotation, were rather low. Such an observation would indicate that this sample contained a large amount of iron sulfides. In fact, the iron and sulfur contents of Cl 4 Conc are seen to be very high. Even though a high copper grade of 15.01 percent was attained in the fourth cleaner concentrate after regrinding (Regr Cl 4 Conc), the Regr Cl Tails are seen to be high in iron and sulfur indicating that iron sulfides were rejected more or less preferentially after regrinding.

Since some magnetic particles were observed with a hand magnet to be present in the concentrates, Davis magnetic tube tests were performed on a one-stage flotation concentrate to investigate if the flotation concentrate might be upgraded in copper. The results are shown in Table 7. Approximately 27 percent by weight of the concentrate was found to be magnetic, low in copper, high in iron, and high in sulfur. It was surmised that the magnetic fraction consisted of monoclinic, or magnetic, pyrrhotite. It is interesting to note that the nonmagnetic fraction analyzed 14.70 percent copper. This observation indicates that the US9001 sample is quite different from most of the other Duluth gabbro samples in which pyrrhotite of magnetic variety was much less.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, Cl Tail, and R Tail samples in both the

TABLE 7. DAVIS MAGNETIC TUBE TEST RESULTS ON A MINUS 200 MESH FLOTATION CONCENTRATE OF US9001 (TEST 4)

Product	% Wt	% Cu	% Ni	% Fe	% S	% Cu Rec	% Ni Rec	% Fe Rec	% S Rec
Magnetic	26.61	1.98	2.00	55.87	37.25	4.66	24.88	41.98	36.85
Nonmagnetic	73.39	14.70	2.19	28.00	23.14	95.34	75.12	58.02	63.15
Composited Head	100.00	11.32	2.13	35.42	26.89				

one-stage grind flotation test and in the two-stage grind flotation test were analyzed by Barringer Research Ltd. The results are given in Tables 8 and 9. In these tables it is seen that the concentration of zinc in the cleaner concentrates was notably increased. The concentrations of silver and mercury also increased to some extent. These increases are apparently due to the close association of these elements with sulfide minerals. Of note is the presence of arsenic (0.005 percent) in the two-stage grind flotation concentrate. The copper, nickel, iron and cobalt analyses by Barringer and by the MRRC are seen to be in reasonably good agreement. The silicon analyses in Table 9 appear to be unreasonably low since the feed and tailing samples were essentially silicates.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were analyzed in a similar manner after one week and one month of standing. Some analyses of these solution samples for trace elements, however, were withheld since all the other samples showed virtually identical trends. The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 10 shows the amounts of residual flotation reagents in the liquors. Tables 11 and 12 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease somewhat from near 8 immediately after flotation to about 7.5 in a month in the one-stage grind flotation

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON US9001 (TEST 6 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.86		1.85		9.08		7.36	
B								
Be	0.00009		0.00004		0.00009		0.00009	
Ca	5.84		1.33		5.85		5.50	
Cu	0.322	0.39	10.3	10.62	0.0773	0.097	0.0124	0.03
Fe	9.04	11.15	36.1	39.94	9.72	12.01	7.98	10.28
Mg	3.64		1.15		3.66		3.58	
Mn	0.110		0.0403		0.112		0.109	
P	0.133		2.06		0.101		0.075	
Ba	0.0822		0.0075		0.0774		0.103	
Se	nd		nd		nd		nd	
As	nd		nd		nd		nd	
Si								
Sr	0.0225		0.00452		0.0235		0.0215	
Zr	0.0096		0.0025		0.0101		0.0113	
Ti	0.964		0.184		0.994		1.05	
V	0.0168		0.0118		0.0196		0.0166	
Zn	0.0152		0.114		0.0124		0.011	
Th	nd		nd		nd		nd	
K	0.49		0.07		0.46		0.47	
Na	2.07		0.4		2.08		2.07	
Cd	nd		nd		nd		nd	
Cr	0.0447		1.92		0.144		0.0257	
Co	0.0096	0.013	0.107	0.128	0.0087	0.012	0.0062	0.010
Ag	nd		0.0032		nd		nd	
Mo	0.0005		0.0085		0.0034		nd	
Ni	0.0888	0.11	1.91	1.94	0.0764	0.11	0.0266	0.04
Pb	nd		nd		nd		nd	
Hg**	0.000006		0.00002				0.000004	

(Continued)

TABLE 8 - CONTINUED (US9001)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
F^-	<1***							
Cl^-	307							
NO_2^-	74							
$PO_4^{\equiv}$	<40							
Br^-	<16							
NO_3^-	112							
$SO_4^{\equiv}$	1600							

* Conventional AA analyses
** 0.000001% = 1 ppb
*** All the anion analysis results in ppm

TABLE 9. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON US9001 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.51		0.653		8.9		8.92	
B	0.15		0.0544		0.123		0.134	
Be	0.00009		0.00001		0.00009		0.00009	
Ca	5.62		0.416		5.71		5.83	
Cu	0.315	0.39	16.1	15.01	0.212	0.21	0.032	0.075
Fe	8.88	12.44	46.2	46.06	9.1	12.75	8.08	11.99
Mg	3.66		0.486		3.62		3.74	
Mn	0.11		0.0212		0.107		0.112	
P	0.133		2.24		0.16		0.072	
Ba	0.103		0.0343		0.0919		0.0956	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
S	nd		0.005		nd		nd	
Si	1.41		0.59		1.18		1.3	
Sr	0.0228		0.00199		0.0232		0.0237	
Zr	0.0111		0.0022		0.0128		0.0085	
Ti	1.0		0.0718		0.959		0.967	
V	0.0174		0.00637		0.0188		0.0165	
Zn	0.0128		0.148		0.0147		0.0097	
Th	nd		nd		0.0007		nd	
K	0.164		0.042		0.126		0.123	
Na	2.05		0.206		2.04		2.14	
Cd	nd		nd		nd		nd	
Cr	0.0178		0.11		0.0671		0.0135	
Co	0.0097	0.018	0.145	0.162	0.0099	0.019	0.0062	0.018
Ag	nd		0.004		nd		nd	
Mo	nd		0.0067		0.0014		nd	
Ni	0.0813	0.10	2.78	2.56	0.101	0.115	0.026	0.035
Pb	nd		nd		nd		nd	
Au**								

* Conventional AA analyses
**0.0000001% = 1 ppb

TABLE 10. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTION OF US9001

Sampling Time	One-stage Grind Flotation (Test 6) pH	KAX ppm	MIBC ppm	Two-stage Grind Flotation (Test 7) pH	KAX ppm	MIBC ppm
Immediately after flotation	7.9	0.29	6.52	7.3	0.32	6.37
After 1 Day	7.8	0.25	4.89	7.1	0.23	4.51
After 1 Week	7.6	0.22	0.00	7.05	0.20	0.00
After 1 Month	7.5	0.10	0.00	7.1	0.12	0.00

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF US9001 (TEST 6 - MINUS 200 MESH GRIND)

	Distilled Water (9-15-77)	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al	nd	0.45	0.45	0.16	0.13	
B	nd	0.049	0.043	0.031	nd	
Ba	nd	nd	nd	nd	0.04	
Be	nd	nd	nd	nd	nd	
Ca	nd	49.3	29.8	32.9	30.1	
Cu	0.021	0.021	0.009	0.005	0.012	
Fe	nd	0.447	0.475	0.078	0.008	
K	nd	11	8	9	8.6	
Mg	0.024	37.5	22.8	26.0	23.6	
Mn	0.0024	0.199	0.0437	0.0097	0.0284	
Na	nd	11	7	7	9	
P	nd	nd	nd	nd	nd	
Se	nd	nd	nd	nd	nd	
Te	nd	nd	nd	nd	nd	
Pb	nd	nd	nd	nd	nd	
Si	nd	3.08	2.91	3.17	5.45	
Sr	nd	0.0774	0.0435	0.0455	0.042	
Ti	nd	0.015	0.010	nd	0.002	
V	nd	0.013	0.007	0.007	0.027	
Zn	0.39	nd	0.64	1.44	0.19	
Th	nd	nd	nd	nd	0.016	
Ag	nd	nd	nd	nd	nd	
As	nd	0.4	0.2	0.2	nd	
Cd	nd	nd	nd	nd	nd	
Co	nd	nd	nd	nd	nd	
Cr	nd	0.015	0.017	0.015	0.078	
Mo	nd	nd	nd	0.04	0.04	
Ni	0.17	0.10	nd	nd	0.25	
Zr	nd	nd	nd	nd	nd	

TABLE 12. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF US9001 (TEST 7 - MINUS 65 MESH GRIND)

	Feed Water	Tailing Water			
		immed.	1 day old	1 week old	1 month old
Al	0.3	0.21	0.11		
B	nd	nd	nd		
Ba	0.07	0.04	0.07		
Be	nd	nd	nd		
Ca	39.2	20.3	19.8		
Cu	0.021	0.008	0.014		
Fe	0.156	0.117	0.032		
K	9.9	7.6	6.9		
Mg	28.0	16.1	15.2		
Mn	0.259	0.0532	0.078		
Na	7	3	3		
P	nd	nd	nd		
Se	nd	nd	nd		
Te	nd	nd	nd		
Pb	nd	nd	nd		
Si	2.94	2.4	2.93		
Sr	0.068	0.0337	0.03		
Ti	0.009	0.004	0.002		
V	0.033	0.018	0.014		
Zn	0.19	0.1	0.14		
Th	0.013	nd	nd		
Ag	nd	nd	nd		
As	nd	0.2	0.2		
Cd	nd	nd	nd		
Co	nd	nd	nd		
Cr	0.095	0.047	0.042		
Mo	nd	0.04	nd		
Ni	1.25	0.23	0.2		
Zr	nd	nd	nd		

and from 7.3 to 7.1 in the two-stage grind flotation. Both the collector (KAX) and the frother (MIBC) decomposed almost completely in one week. The trace element analyses of the pulp solutions in Tables 11 and 12 showed that the concentration of copper remained near 10 ppb throughout the period. In fact, these values were lower than those in the distilled water used at the time. The decrease in the presence of the ore sample may be interpreted to be due to adsorption and that upon the addition of flotation reagents to the precipitation of insoluble copper xanthate. The concentrations of nickel ions in the pulp solutions remained rather high ranging 0.1 to 1.25 ppm in some samples, but they appeared to decrease upon aging due perhaps to some exchange reactions with less noble elements such as zinc. The zinc-ion concentration remained at a few tenths of one ppm, but reached 1.44 ppm on one occasion. It should be noted in these tables that arsenic was present in the range of 0.2 to 0.4 ppm in some of the pulp solutions. Since these values are barely above the limit of detection (0.14 ppm), the significance of such an observation should be carefully evaluated with further testing.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of Table 6. The size distributions of concentrates in the same range were determined by microscreening (Table 13). The data in the 'subsieve' range are of particular interest since the air-borne dusts are said to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200-mesh grind would have about 5 percent by weight of minus 5 μm particles. At a 65-mesh grind, however, minus 5 μm particles would be about 2.5 percent.

TABLE 13. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF US9001

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	41.45	-
+20	78.99	26.58	81.58
+10	10.07	16.30	9.19
+5	5.18	15.67**	4.54
-5	5.76	-	4.69
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	20.28	-
+20	92.77	39.46	93.47
+10	3.70	22.40	3.00
+5	2.11	17.86**	1.63
-5	1.42	-	1.90

* Cl 4 Conc and Regr Cl 4 Conc, respectively
**Minus 10 µm

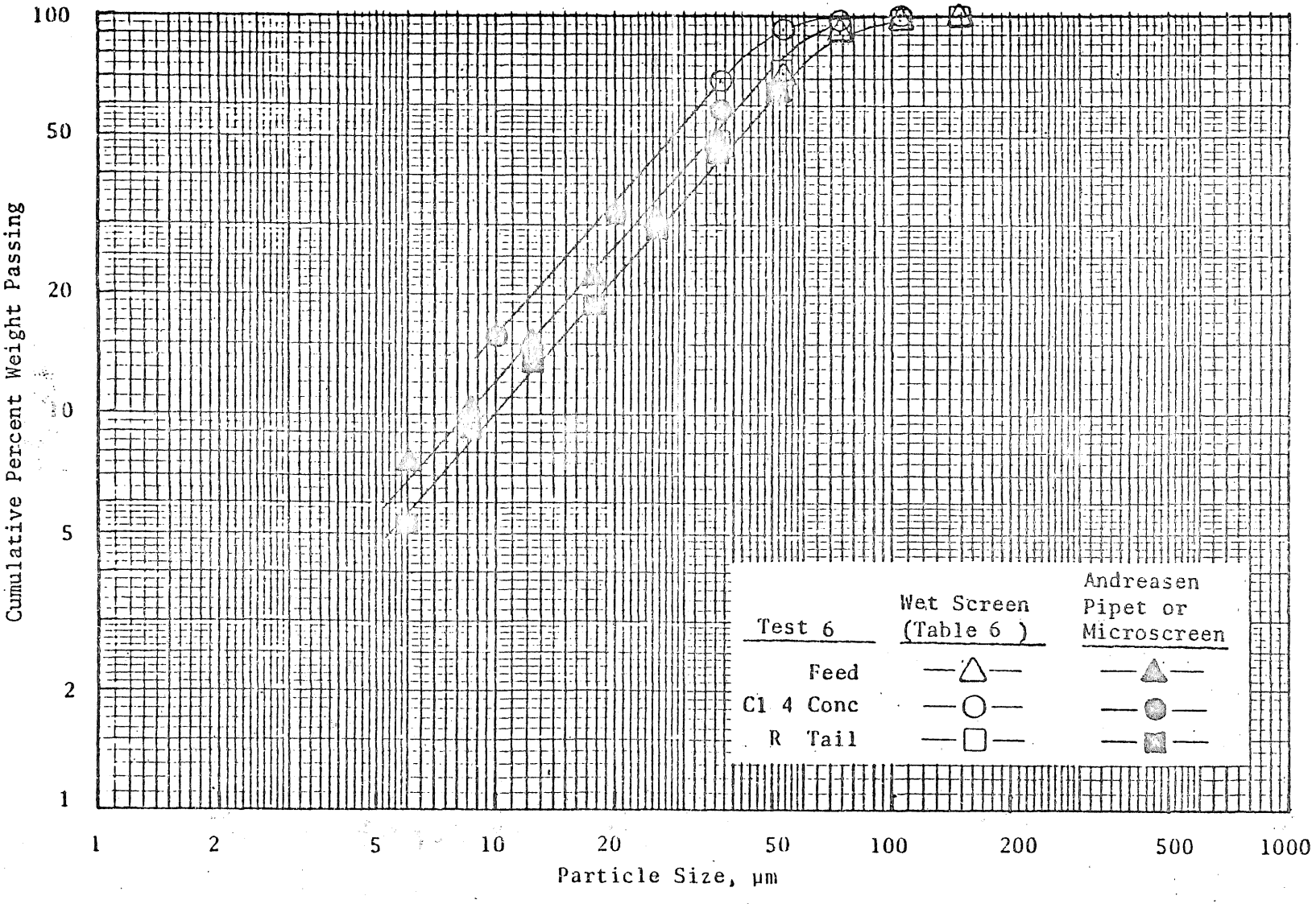


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF US9001 (MINUS 200 MESH GRIND)

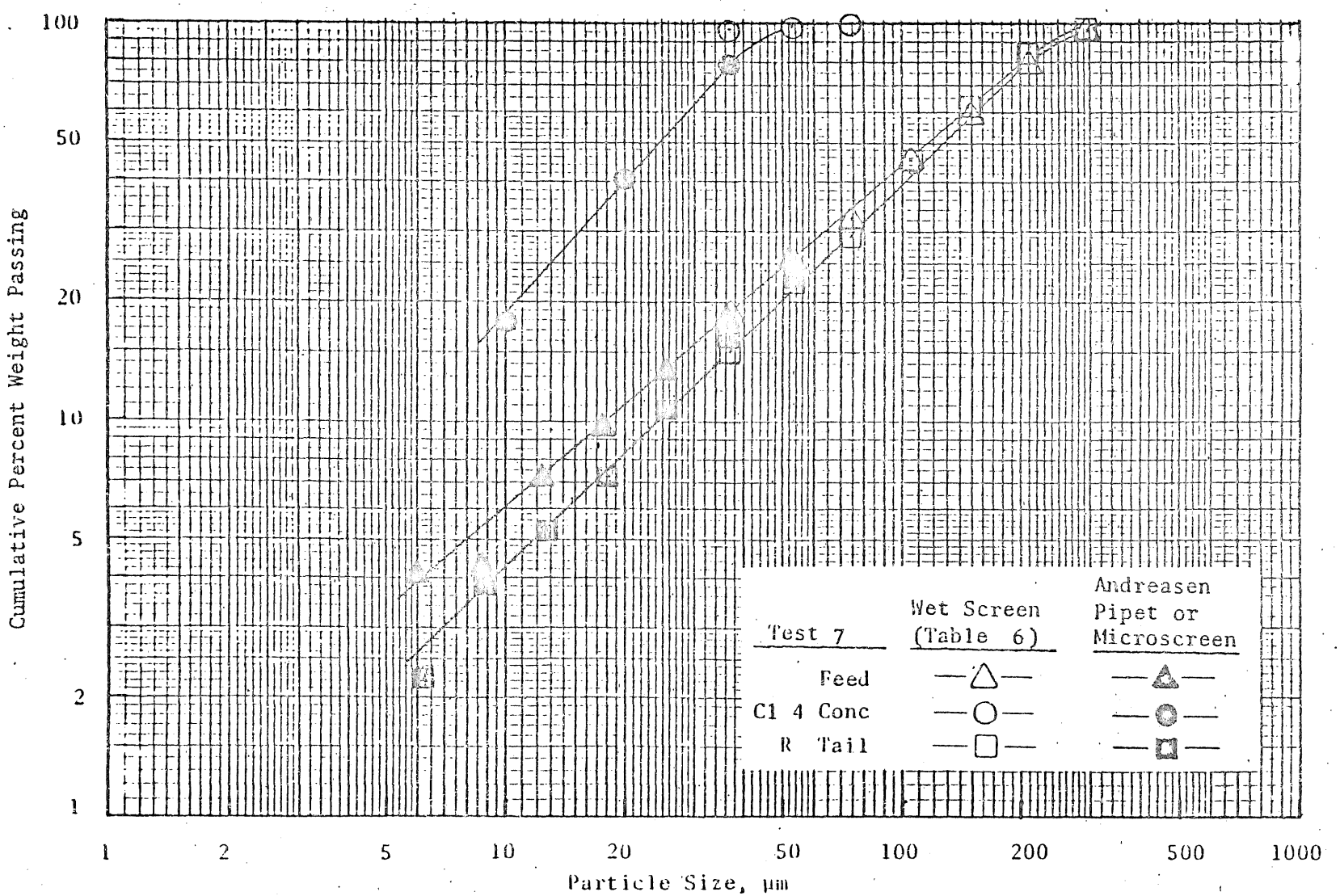


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF US9001
(MINUS 65 MESH FOR FEED AND 'LING, MINUS 270 MESH FOR CONCENTRATE)

The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

To investigate how various elements are distributed over different size fractions in the 'subsieve' range the feed and the rougher tailing samples were separated into +20, 20/10, 10/5 and -5 μm fractions by the sedimentation sizing method, and the size distributions of the concentrates were determined by microscreening to 10 μm. Each size fraction of the feed, concentrate and rougher tailing was analyzed by Barringer Research Ltd. and the results are given in Table 14. In the rougher tailing of this sample virtually all heavy metals including copper are seen to be, more or less, evenly distributed over all the sizes. Only the nickel content in the minus 5-μm fraction in the rougher tailing was about twice as high as the other fraction. It is also noted that small amounts of arsenic were present in the finer fractions of the flotation concentrate.

TABLE 14. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT ON SIZE FRACTIONS OF FLOTATION PRODUCTS OF US9001 (TEST 6 - ONE-STAGE GRIND FLOTATION)

	Feed				Concentrate				Rougher Tailing			
	+20 μm	20/10 μm	10/5 μm	-5 μm	+37 μm	37/20 μm	20/10 μm	-10 μm	+20 μm	20/10 μm	10/5 μm	-5 μm
Al	12.0	11.0	11.0	10.5	6.89	2.44	1.25	0.773	10.1	11.8	11.2	10.2
B	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Be	0.0001	0.00011	0.0001	0.0001	0.00011	nd	nd	nd	0.0001	0.00012	0.00011	0.00011
Ca	7.92	6.69	6.55	5.93	3.33	1.36	0.72	0.454	6.42	7.08	6.72	5.88
Cu	0.35	0.415	0.5	0.511	7.57	16.5	21.4	24.3	0.0714	0.0608	0.0615	0.0894
Fe	13.5	8.98	8.82	9.9	17.5	25.2	27.5	26.9	10.6	9.14	9.25	10.1
Mg	5.52	3.47	3.34	3.64	3.55	2.32	2.11	1.58	4.28	3.64	3.61	3.72
Mn	0.153	0.105	0.101	0.114	0.0759	0.0472	0.0377	0.0268	0.136	0.111	0.11	0.115
P	0.02	0.033	0.016	0.019	nd	nd	nd	nd	0.066	0.092	0.098	0.076
Ba	0.138	0.209	0.143	0.109	0.0062	0.0053	0.0043	0.0075	0.196	0.215	0.209	0.0969
Se												
Te												
As	nd	nd	nd	nd	nd	nd	0.002	0.008	nd	nd	nd	nd
Si	1.88	3.06	3.09	3.13	1.46	0.436	0.397	0.777	2.83	3.01	2.93	0.948
Sr	0.0329	0.0297	0.0304	0.0276	0.0151	0.00547	0.00242	0.00181	0.0268	0.0313	0.0303	0.0257
Zr	0.0127	0.0155	0.0144	0.0123	0.00607	0.00344	0.00261	0.00216	0.0149	0.0169	0.0155	0.00804
Ti	1.25	0.925	0.942	0.934	0.283	0.179	0.14	0.121	1.27	1.11	1.14	1.05
V	0.0227	0.0147	0.0141	0.0141	0.0199	0.0113	0.00957	0.00758	0.0191	0.0161	0.0159	0.0152
Zn	0.0182	0.0127	0.0148	0.0304	0.0268	0.0496	0.0792	0.219	0.0131	0.0124	0.0124	0.0179
Th	0.0003	0.00072	0.00059	0.00069	0.00021	nd	nd	nd	0.00055	0.00063	0.00069	0.00057
K	0.858	0.883	0.88	0.995	0.443	0.1	0.024	0.02	0.791	0.995	0.914	1.01
Na	2.93	2.79	2.84	2.57	1.38	0.5	0.27	0.23	2.64	2.97	2.82	2.19
Cd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cr	0.0468	0.0805	0.0674	0.0685	0.0107	0.00246	0.0103	0.0772	0.0183	0.0634	0.105	0.104
Co	0.0115	0.0099	0.0099	0.0139	0.0457	0.11	0.124	0.0768	0.0082	0.0064	0.0068	0.0099
Ag	0.0002	0.00022	0.00025	0.00038	0.00137	0.0032	0.00532	0.00759	0.00014	0.00012	0.00013	0.00021
Mo	nd	0.0012	nd	0.002	0.0042	0.0072	0.012	0.0178	nd	nd	0.004	0.0039
Ni	0.101	0.105	0.104	0.174	0.851	2.23	2.48	1.34	0.0362	0.0388	0.0491	0.106
Pb	nd	nd	nd	nd	0.0035	0.006	0.0095	0.029	nd	nd	nd	nd

3.5 FLOTATION TESTS ON AX9001 SAMPLE

Sample Description

A Minnamax Leach Pad sample, labeled AX9001, weighing approximately 239 kilograms, was received on August 4, 1977 from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. The sample was reported to be taken from leach pad number one at the Minnamax shaft site. Sampling was accomplished by taking specimens at about ten-foot intervals around the perimeter of the pad as well as over the top of the pad for its entire length. No effort was made to select a sample on the basis of its sulfide content.

The whole sample was stage-crushed to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF AX9001 SAMPLE

Constituent	Percent
Copper (Cu)	0.31
Nickel (Ni)	0.085
Cobalt (Co)	0.018
Iron (Fe)	9.50
Sulfur (S)	0.66
Titanium dioxide (TiO_2)	2.31
Graphite carbon (C)	0.114

Grinding Characteristics

The grinding characteristics of the AX9001 sample were investigated by grinding 1200-gram batches of minus 10-mesh feed in a stainless steel laboratory rod mill at 50 percent solids for various periods of time. The size dsitributions of the minus 10-mesh feed and of a sample ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in

TABLE 2. SCREEN ANALYSIS OF AX9001 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 Mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	0.5	100.0	-	-	-	-	-	-	-	-
+14	15.4	99.5	-	-	-	-	-	-	-	-
+20	9.0	84.1	-	-	-	-	-	-	-	-
+28	20.5	75.1	-	-	-	-	-	-	-	-
+35	9.7	54.6	-	-	-	-	-	-	-	-
+48	8.6	44.9	1.4	100.0	-	-	-	-	-	-
+65	7.1	36.3	7.6	98.6	3.0	100.0	-	-	-	-
+100	7.2	29.2	23.5	91.0	14.3	97.0	0.9	100.0	-	-
+150	8.6	22.0	19.3	67.5	25.8	82.7	17.3	99.1	0.6	100.0
+200	3.9	13.4	18.1	48.2	13.1	56.9	27.0	81.8	7.1	99.4
+270	3.6	9.5	4.9	30.1	11.0	43.8	11.3	54.8	19.3	92.3
+325	0.7	5.9	3.3	25.2	7.2	32.8	6.7	43.5	10.9	73.0
+400	0.9	5.2	3.8	21.9	4.3	25.6	5.5	36.8	16.0	62.1
+500	0.8	4.3	7.1	18.1	4.8	21.3	8.9	31.3	13.4	46.1
-500	3.5	3.5	11.0	11.0	16.5	16.5	22.4	22.4	32.7	32.7

Figure 1. The size distribution data of the ground batches are seen to be represented by straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.97. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF AX9001 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50 PERCENT SOLIDS)

Nominal Mesh-of-Grind	Grind Time Minutes	Size Modulus k, μm	80% passing μm
-10 mesh	0	-	970
-48 mesh	15	237	190
-65 mesh	20	175	140
-100 mesh	30	131	102
-200 mesh	60	78	63

Preliminary Flotation Tests

The effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh, and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed

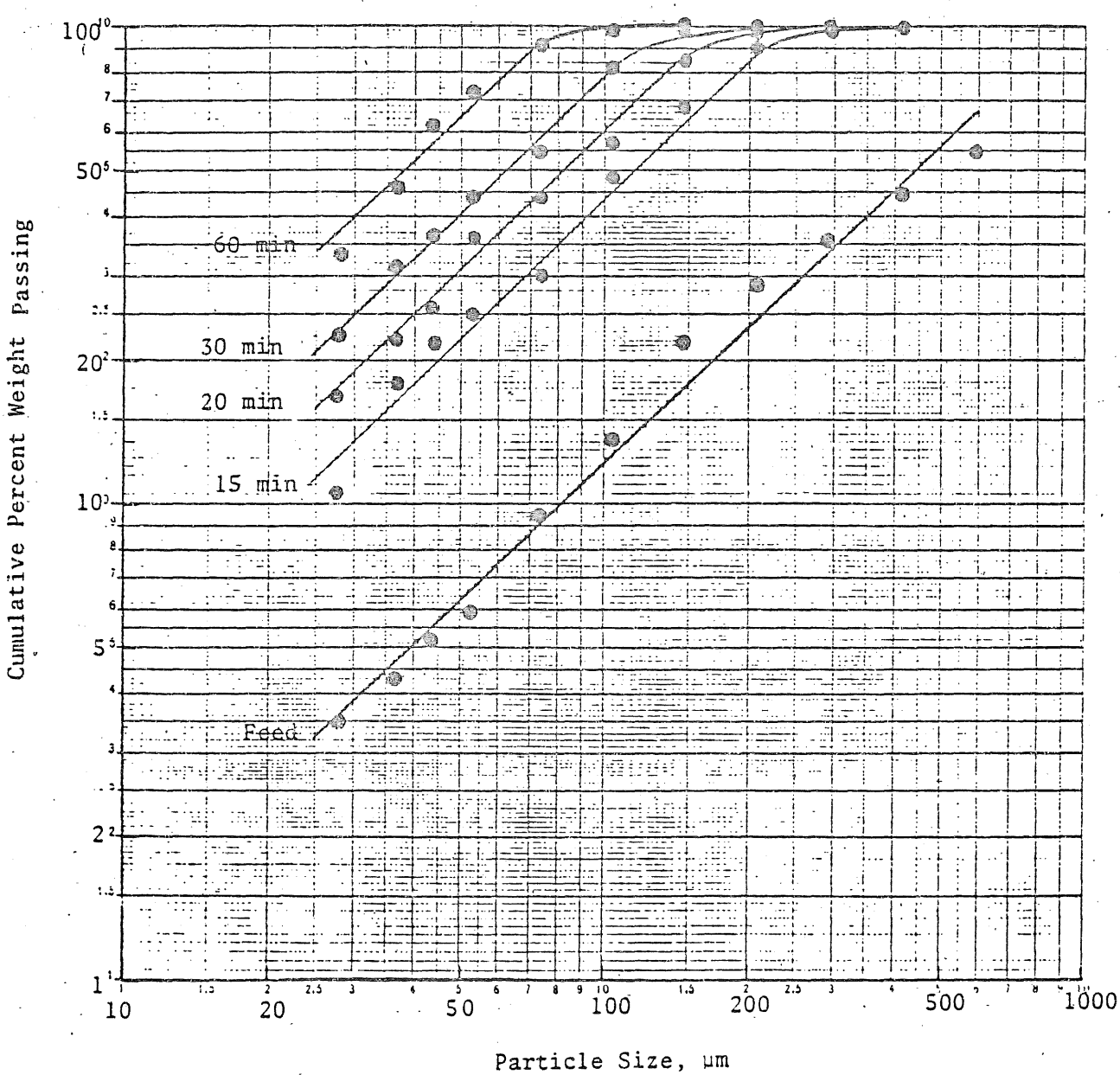


FIGURE 1. SIZE DISTRIBUTIONS OF AX9001 SAMPLE AS A FUNCTION OF GRINDING TIME

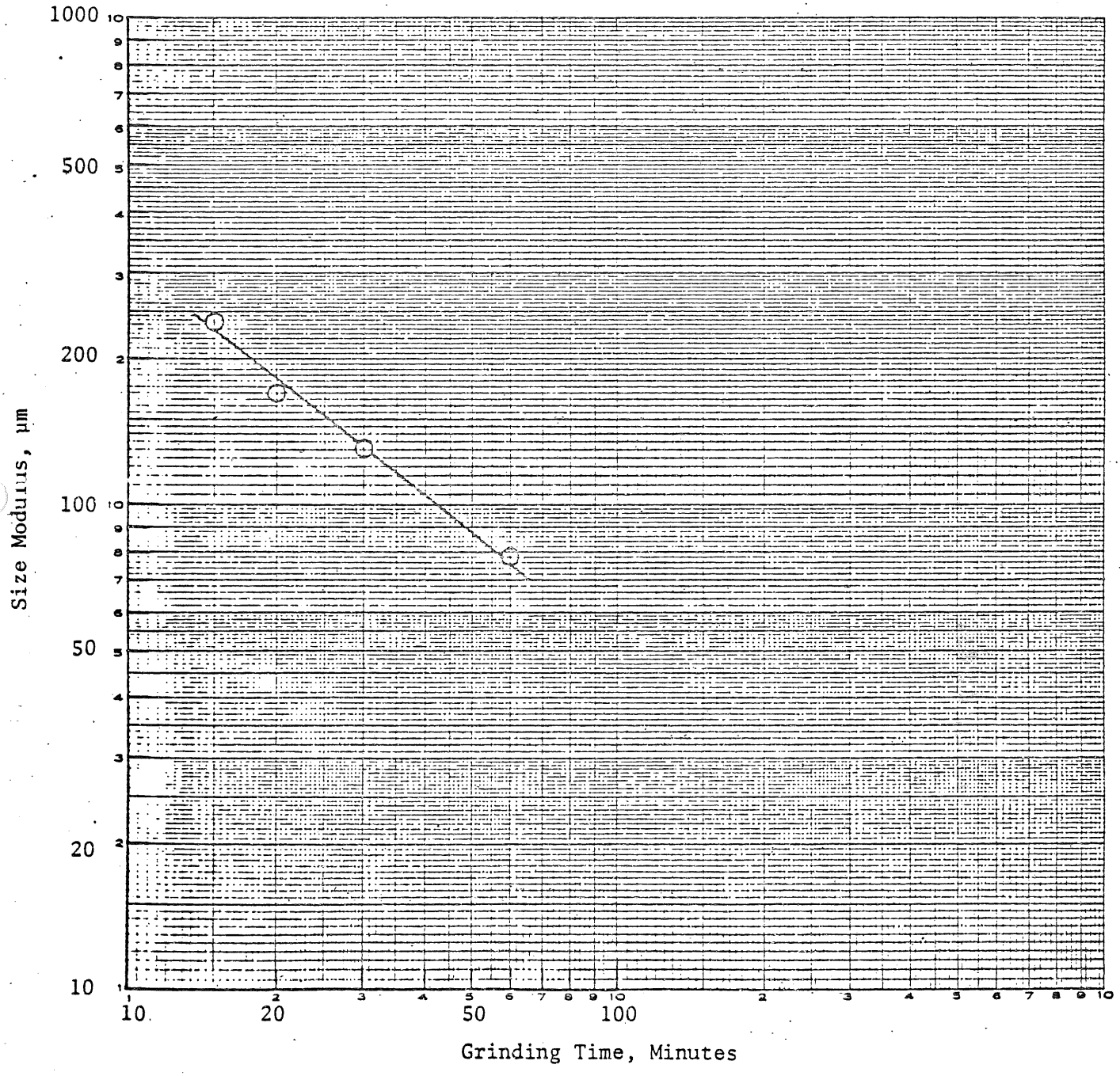


FIGURE 2. SIZE MODULI OF AX9001 SAMPLE AS A FUNCTION OF GRINDING TIME

at 3 minutes. The results of these flotation tests are given in Table 4.

It is apparent in Table 4 that both the losses of copper and of nickel to the R Tails remained approximately constant at about 12 percent and 35 percent, respectively, for all the mesh-of-grinds. It is also noted that the concentrate grade improved as the mesh-of-grind became finer and after four cleaner stages analyzed in excess of 16 percent copper and 1.6 percent nickel at 200-mesh grind. In the two-stage grind flotation test the concentrate grade exceeded 16 percent copper after regrinding and three cleaner stages.

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 91.43%, 69.05%, and 94.31%, respectively, at 200 mesh (one-stage grind flotation), and were 83.55%, 68.26% and 88.86%, respectively, at 65 mesh (two-stage grind flotation). The flotation concentrate could be upgraded to 13.20 percent copper and 1.88 percent nickel in the one-stage grind flotation after four cleanings, whereas in the two-stage grind flotation the concentrate was upgraded to 14.91 percent copper and 2.75 percent nickel after two cleanings following regrinding. The sum of the copper, nickel, cobalt, iron, and sulfur contents may be asssumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The fourth

TABLE 4. EFFECT OF MESH-OF-GRIND ON AX9001

Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Cleaner - MIBC 0.06 lb/ton

Flotation Time: Rougher 10 min, Cleaner 5 min

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	2.11	10.18	1.42	73.39	31.18	2.11	10.18	1.42	73.39	31.18
		Cl 4 Tail	0.50	1.36	1.10	2.32	5.72	2.61	8.49	1.36	75.71	36.90
		Cl 3 Tail	1.63	0.89	0.85	4.95	14.45	4.24	5.57	1.17	80.66	51.35
		Cl 2 Tail	1.46	0.52	0.38	2.60	5.82	5.70	4.28	0.965	83.26	57.17
		Cl 1 Tail	5.68	0.16	0.10	3.11	5.93	11.38	2.22	0.533	86.37	63.10
		R Tail	88.62	0.045	0.04	13.63	36.90	100.00	0.30	0.096	100.00	100.00
2	65	Cl 4 Conc	2.51	10.06	1.68	79.05	43.02	2.51	10.06	1.68	79.05	43.02
		Cl 4 Tail	1.05	0.99	0.61	3.26	6.52	3.56	7.38	1.37	82.31	49.54
		Cl 3 Tail	0.57	0.85	0.67	1.53	3.87	4.13	6.48	1.27	83.84	53.41
		Cl 2 Tail	1.17	0.55	0.33	2.00	3.98	5.30	5.17	1.06	85.84	57.39
		Cl 1 Tail	6.64	0.15	0.10	3.13	6.73	11.94	2.38	0.527	88.97	64.12
		R Tail	88.06	0.04	0.04	11.03	35.88	100.00	0.32	0.098	100.00	100.00
3	100	Cl 4 Conc	1.71	13.22	1.66	73.66	31.99	1.71	13.22	1.66	73.66	31.99
		Cl 4 Tail	0.46	1.40	1.44	2.09	7.43	2.17	10.71	1.61	75.75	39.42
		Cl 3 Tail	0.96	0.82	0.79	2.58	8.56	3.13	7.68	1.36	78.33	47.98
		Cl 2 Tail	3.47	0.50	0.30	5.67	11.71	6.60	3.90	0.803	84.00	59.69
		Cl 1 Tail	7.44	0.14	0.10	3.39	8.33	14.04	1.91	0.430	87.39	68.02
		R Tail	85.96	0.045	0.033	12.61	31.98	100.00	0.31	0.089	100.00	100.00
4	200	Cl 4 Conc	1.42	16.20	1.60	75.19	21.57	1.42	16.20	1.60	75.19	21.57
		Cl 4 Tail	0.33	0.98	1.28	1.05	3.99	1.75	13.33	1.54	76.24	25.56
		Cl 3 Tail	1.00	0.35	0.53	1.14	5.04	2.75	8.61	1.17	77.38	30.60
		Cl 2 Tail	3.63	0.20	0.29	2.39	9.98	6.38	3.82	0.669	79.77	40.58
		Cl 1 Tail	20.96	0.08	0.09	5.49	17.97	27.34	0.95	0.225	85.26	58.55
		R Tail	72.66	0.062	0.06	14.74	41.45	100.00	0.31	0.105	100.00	100.00
5 Rghr	65	Regr Cl 4 C	1.16	19.95	2.06	70.04	22.81	1.16	19.95	2.06	70.04	22.81
Regr	270	Regr Cl 4 T	0.06	2.45	2.39	0.45	1.34	1.22	19.09	2.07	70.49	24.15
		Regr Cl 3 T	0.19	1.42	1.90	0.82	3.43	1.41	16.71	2.05	71.31	27.58
		Regr Cl 2 T	0.54	0.72	1.26	1.18	6.49	1.95	12.28	1.83	72.49	34.07
		Regr Cl 1 T	2.40	0.51	0.50	3.69	11.45	4.35	5.79	1.10	76.18	45.52
		Cl Tail	5.92	0.33	0.19	5.90	10.78	10.27	2.64	0.58	82.08	56.30
		R Tail	89.73	0.066	0.051	17.92	43.70	100.00	0.33	0.105	100.00	100.00

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON AX9001

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 6 Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 23°C Rougher pH: 9.4							
Cl 4 Conc	2.08	13.20	1.88	0.088	26.50	19.18	2.85
Cl 4 Tail	0.64	0.49	0.49	0.028	15.15	3.02	-
Cl 3 Tail	1.19	0.28	0.20	0.020	14.55	1.89	-
Cl 2 Tail	3.22	0.11	0.09	0.014	13.40	1.26	-
Cl 1 Tail	12.40	0.064	0.043	0.014	11.96	0.53	-
R Tail	80.47	0.034	0.028	0.013	10.98	0.041	-
Flotation Feed	100.00	0.38	0.10	0.014	12.00	0.69	0.17
Test No. 7 Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 24°C Rougher pH: 9.4							
Regr Cl 4 Conc	1.50	17.58	2.78	0.13	29.59	24.95	5.00
Regr Cl 4 Tail	0.11	1.65	3.58	0.175	19.98	9.83	-
Regr Cl 3 Tail	0.19	1.45	2.05	0.11	18.25	8.05	-
Regr Cl 2 Tail	0.41	0.64	0.53	0.032	13.12	3.56	-
Regr Cl 1 Tail	3.18	0.29	0.124	0.019	11.75	2.54	-
Cl Tail	5.57	0.25	0.102	0.013	12.30	1.29	-
R Tail	89.04	0.065	0.032	0.011	10.53	0.080	-
Flotation Feed	100.00	0.36	0.085	0.011	10.89	0.62	-

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION ON AX9001

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 6 One-stage Grind Flotation																	
Cleaner 4	2.08	13.20	1.88	0.088	26.50	19.18	85.87	53.79	12.08	4.93	68.77	97.92	0.046	0.034	0.013	10.83	0.185
Cleaner 3	2.72	10.21	1.55	0.074	23.90	15.38	86.84	58.05	13.42	5.83	72.10	97.28	0.043	0.031	0.013	10.80	0.166
Cleaner 2	3.91	7.19	1.14	0.056	20.97	11.27	87.87	61.35	14.26	7.35	75.98	96.09	0.040	0.029	0.013	10.76	0.145
Cleaner 1	7.13	3.99	0.630	0.038	17.53	6.75	88.96	61.76	18.12	11.20	82.98	92.87	0.038	0.030	0.013	10.67	0.107
Rougher	19.53	1.50	0.257	0.023	13.98	2.80	91.43	69.05	29.53	24.46	94.31	80.47	0.034	0.028	0.013	10.98	0.041
Test No. 7 Two-stage Grind Flotation																	
Regr Cleaner 4	1.50	17.58	2.78	0.13	29.59	24.95	74.94	46.44	14.70	4.00	58.59	98.50	0.090	0.049	0.012	10.71	0.269
Regr Cleaner 3	1.61	16.49	2.83	0.138	28.57	23.92	75.45	50.78	16.17	4.18	60.28	98.39	0.088	0.045	0.012	10.70	0.258
Regr Cleaner 2	1.80	14.91	2.75	0.133	27.78	22.24	76.25	55.12	17.64	4.54	62.67	98.20	0.085	0.041	0.011	10.68	0.243
Regr Cleaner 1	2.21	12.26	2.34	0.113	24.89	18.79	76.99	57.57	18.38	5.00	64.96	97.79	0.083	0.039	0.011	10.68	0.229
Cleaner	5.39	5.20	1.03	0.058	17.07	9.20	79.60	61.91	22.79	8.37	77.61	94.61	0.076	0.036	0.011	10.64	0.151
Rougher	10.96	2.68	0.559	0.035	14.69	5.18	83.55	68.26	27.94	14.65	88.86	89.04	0.065	0.032	0.011	10.53	0.080

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF AX9001

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+150	1.20	-	1.23
+200	10.53	2.60	8.07
+270	21.11	19.40	21.61
+400	18.77	22.40	27.16
-400	48.39	55.60	41.93
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	4.00	-	1.50
+65	14.26	-	7.71
+100	18.39	-	20.69
+150	13.30	-	18.44
+200	15.22	-	18.40
+270	7.30	4.22	8.04
+400	6.87	13.92	8.12
-400	20.66	81.86	17.10

*Cl 4 Conc and Regr Cl 4 Conc, respectively

cleaner concentrate (Cl 4 Conc) in the one-stage grind flotation would then have 39.2 percent gangue and the reground second cleaner (Regr Cl 2 Conc) in the two-stage grind flotation would have 32.2 percent gangue.

A Davis magnetic tube test was performed on a Cl 4 Conc sample to explore the feasibility of a copper-nickel separation, but the magnetic concentrate amounted to only 2.94 percent by weight. Hence, chemical analyses on the magnetic separation products were not made. Evidently, the pyrrhotite in the present sample is mainly the nonmagnetic variety.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, Cl Tail, and R Tail samples in both the one-stage grind flotation test and in the two-stage grind flotation test were analyzed by Barringer Research Ltd. The results are given in Tables 7 and 8. In these tables it is seen that the concentration of zinc in the cleaner concentrates was notably increased. The concentrations of silver and lead also increased to some extent. These increases are apparently due to the close association of these elements with sulfide minerals. The copper, nickel, iron and cobalt analyses by Barringer and by the MRRC are seen to be in reasonably good agreement. The silicon analyses in Tables 7 and 8 appear to be unreasonably low since the feed and tailing samples were essentially silicates.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the

TABLE 7. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9001 (TEST 6 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.63		3.43		8.65		8.48	
B	0.14		0.0473		0.137		0.135	
Be	0.00008		0.00005		0.0001		0.00008	
Ca	5.46		1.81		5.4		5.42	
Cu	0.308	0.38	14.1	13.20	0.043	0.064	0.0188	0.034
Fe	0.936	12.00	1.87	26.50	0.915	11.96	0.886	10.98
Mg	4.26		2.68		4.07		4.2	
Mn	0.122		0.0506		0.116		0.121	
P	0.11		2.25		0.066		0.052	
Ba	0.0955		0.023		0.0953		0.0934	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
As	nd		nd		nd		nd	
Si	1.33		0.319		1.34		1.31	
Sr	0.0268		0.00797		0.0253		0.0259	
Zr	0.0072		0.0031		0.0074		0.0075	
Ti	1.4		0.229		1.23		1.71	
V	0.0273		0.0145		0.0255		0.0275	
Zn	0.0203		0.143		0.015		0.0144	
Th	nd		nd		nd		nd	
K	0.084		0.084		0.163		0.123	
Na	1.91		0.606		1.85		1.92	
Cd	nd		nd		nd		nd	
Cr	0.0466		0.0136		0.0771		0.0294	
Co	0.0084	0.014	0.0755	0.088	0.0064	0.014	0.0062	0.013
Ag	nd		0.0037		nd		nd	
Mo	0.0002		0.0071		0.0016		nd	
Ni	0.0762	0.10	1.85	1.88	0.0372	0.043	0.0221	0.028
Pb	nd		0.0079		nd		nd	
Hg**								

*Conventional AA analyses
**0.0000001% = 1 ppb

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9001 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.22		1.93		8.09		8.4	
B	0.125		0.0292		0.138		0.131	
Be	0.00008		0.00004		0.00011		0.00008	
Ca	5.25		0.942		4.93		5.36	
Cu	0.284	0.36	18.3	17.58	0.229	0.25	0.0275	0.065
Fe	9.11	10.89	22.0	25.59	10.1	12.30	9.18	10.53
Mg	4.17		1.77		4.27		4.29	
Mn	0.119		0.0295		0.118		0.127	
P	0.111		2.85		0.107		0.056	
Ba	0.0865		0.0076		0.0961		0.0913	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
As	nd		nd		nd		nd	
Si	1.22		0.785		1.34		1.26	
Sr	0.0246		0.0038		0.0231		0.0257	
Zr	0.0064		0.0023		0.0085		0.0074	
Ti	1.38		0.13		1.1		1.88	
V	0.0266		0.0107		0.0276		0.0287	
Zn	0.0152		0.18		0.0193		0.013	
Th	nd		nd		nd		nd	
K	0.162		0.085		0.164		0.12	
Na	1.8		0.322		1.65		1.88	
Cd	nd		nd		nd		nd	
Cr	0.0169		0.00983		0.0561		0.018	
Co	0.0081	0.011	0.11	0.13	0.0092	0.013	0.0065	0.011
Ag	nd		0.0048		nd		nd	
Mo	nd		0.0119		0.0004		nd	
Ni	0.0636	0.085	2.81	2.78	0.0931	0.102	0.0223	0.032
Pb	nd		0.0121		nd		nd	
Au**								

* Conventional AA analyses
**0.0000001% = 1 ppb

effect of tailings on the quality of the water in a tailing pond. The pulp solutions were taken in a similar manner after one week and one month of standing, but only a few selected solution samples were analyzed for trace elements since all the other samples showed virtually identical trends. The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 9 shows the amounts of residual flotation reagents in the liquors. Tables 10 and 11 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease somewhat from near 9 immediately after flotation to about 8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed almost completely in one month. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors. Of particular interest in Table 10 is the fact that the concentration of copper ion in the pulp solution immediately after flotation was rather high, 150 ppb, and that the concentration of copper decreased to 22 ppb after one month of aging. The decrease in the concentration in the presence of the ore sample may be interpreted to be due to adsorption and to some exchange reactions with less noble elements, such as zinc. In fact, the zinc-ion concentration increased from below the limit of detection (19 ppb) to 0.55 ppm in a month. The concentration of nickel remained below the limit of detection (90 ppb) in these tests.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of Table 6. The size distributions of concentrates in the same range were determined by microscreening (Table 12). The data in the 'subsieve' range are of particular

TABLE 9. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTIONS OF AX9001

Sampling Time	One-stage Grind Flotation (Test 6)			Two-stage Grind Flotation (Test 7)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	9.0	1.99	11.18	9.1	1.97	9.19
After 1 Day	8.7	1.27	9.36	8.5	0.66	8.38
After 1 Week	8.1	1.04	2.35	7.9	0.38	1.11
After 1 Month	8.0	0.27	0.00	7.8	0.27	0.00

TABLE 10. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9001 (TEST 6 - MINUS 200 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		1.94	1.12			0.26
B		nd	nd			10.0
Ba		0.04	0.04			0.05
Be		nd	nd			nd
Ca		4.34	6.8			12.8
Cu		0.023	0.15			0.022
Fe		1.82	0.883			0.081
K		5.2	6.4			10.3
Mg		1.67	1.99			2.67
Mn		nd	nd			0.012
Na		32	24			19
P		nd	nd			nd
Se		nd	nd			nd
Te		nd	nd			nd
Pb		nd	nd			nd
Si		5.04	3.9			4.66
Sr		0.0124	0.0179			0.0295
Ti		0.025	0.016			0.002
V		0.012	0.007			0.006
Zn		0.1	nd			0.55
Th		nd	nd			nd
Ag		nd	nd			nd
As		nd	nd			nd
Cd		nd	nd			nd
Co		nd	nd			nd
Cr		0.011	nd			0.014
Mo		0.08	0.12			nd
Ni		nd	nd			nd
Zr		0.001	nd			nd

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9001 (TEST 7 - MINUS 65 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 day old	1 month old
Al		1.57	0.96			
B		nd	nd			
Ba		nd	nd			
Be		nd	nd			
Ca		4.63	6.59			
Cu		0.023	0.015			
Fe		1.09	0.658			
K		5.4	6.9			
Mg		1.39	2.04			
Mn		nd	nd			
Na		28	17			
P		nd	nd			
Se		nd	nd			
Te		nd	nd			
Pb		nd	nd			
Si		3.68	3.92			
Sr		0.0142	0.0179			
Ti		0.019	0.023			
V		0.008	0.006			
Zn		nd	nd			
Th		nd	nd			
Ag		nd	nd			
As		nd	nd			
Cd		nd	nd			
Co		nd	nd			
Cr		nd	nd			
Mo		0.04	0.04			
Ni		nd	nd			
Zr		nd	nd			

TABLE 12. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF AX9001

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	49.19	-
+20	77.64	25.35	84.13
+10	11.26	13.12	9.93
+5	4.74	12.34**	3.39
-5	6.36	-	2.55
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	27.65	-
+20	91.25	37.01	92.41
+10	4.04	16.03	3.38
+5	1.71	19.31**	1.50
-5	3.00	-	2.71

*C1 4 Conc and Regr C1 4 Conc, respectively
**Minus 10 µm

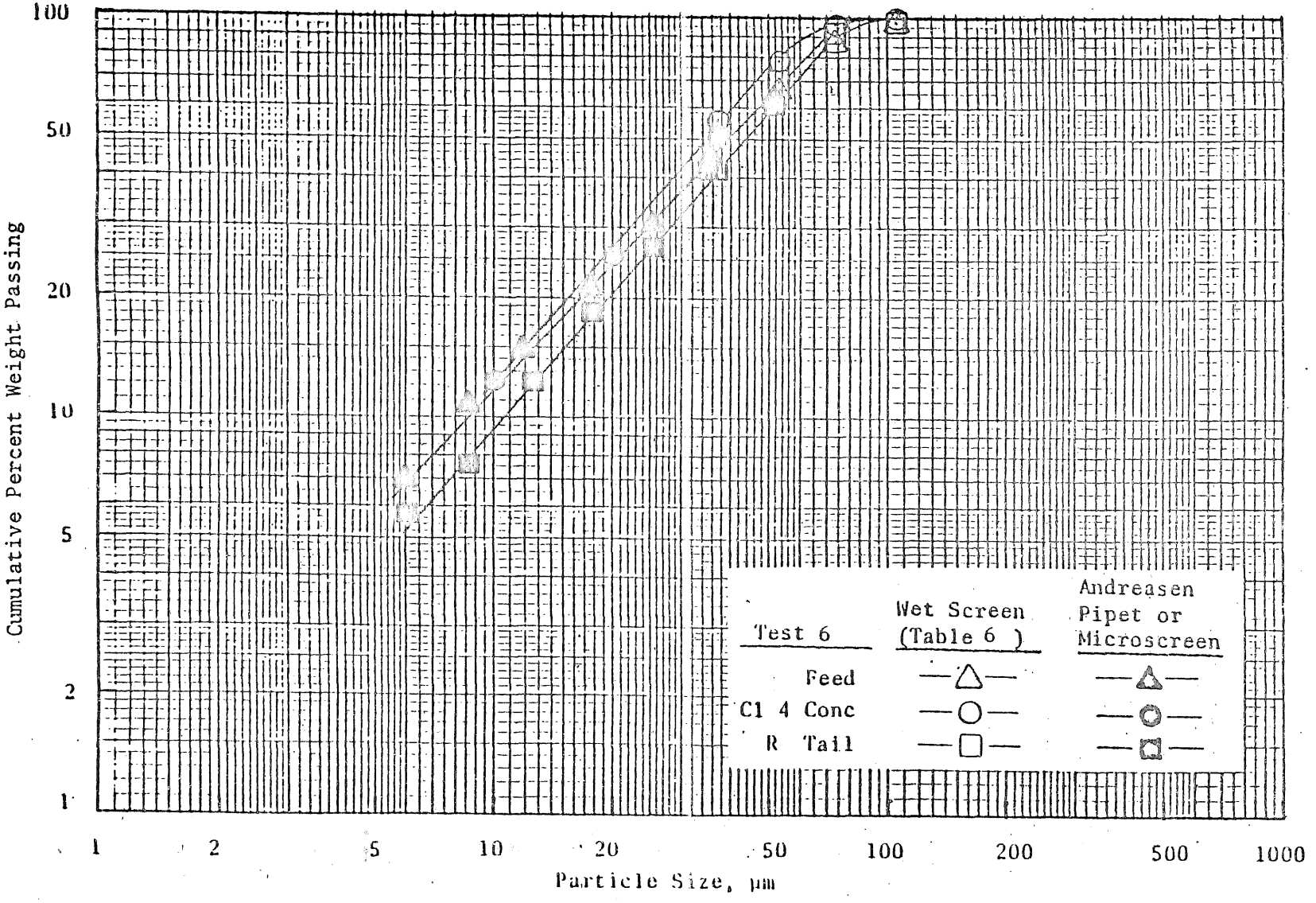


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF AX9001 (MINUS 200 MESH GRIND)

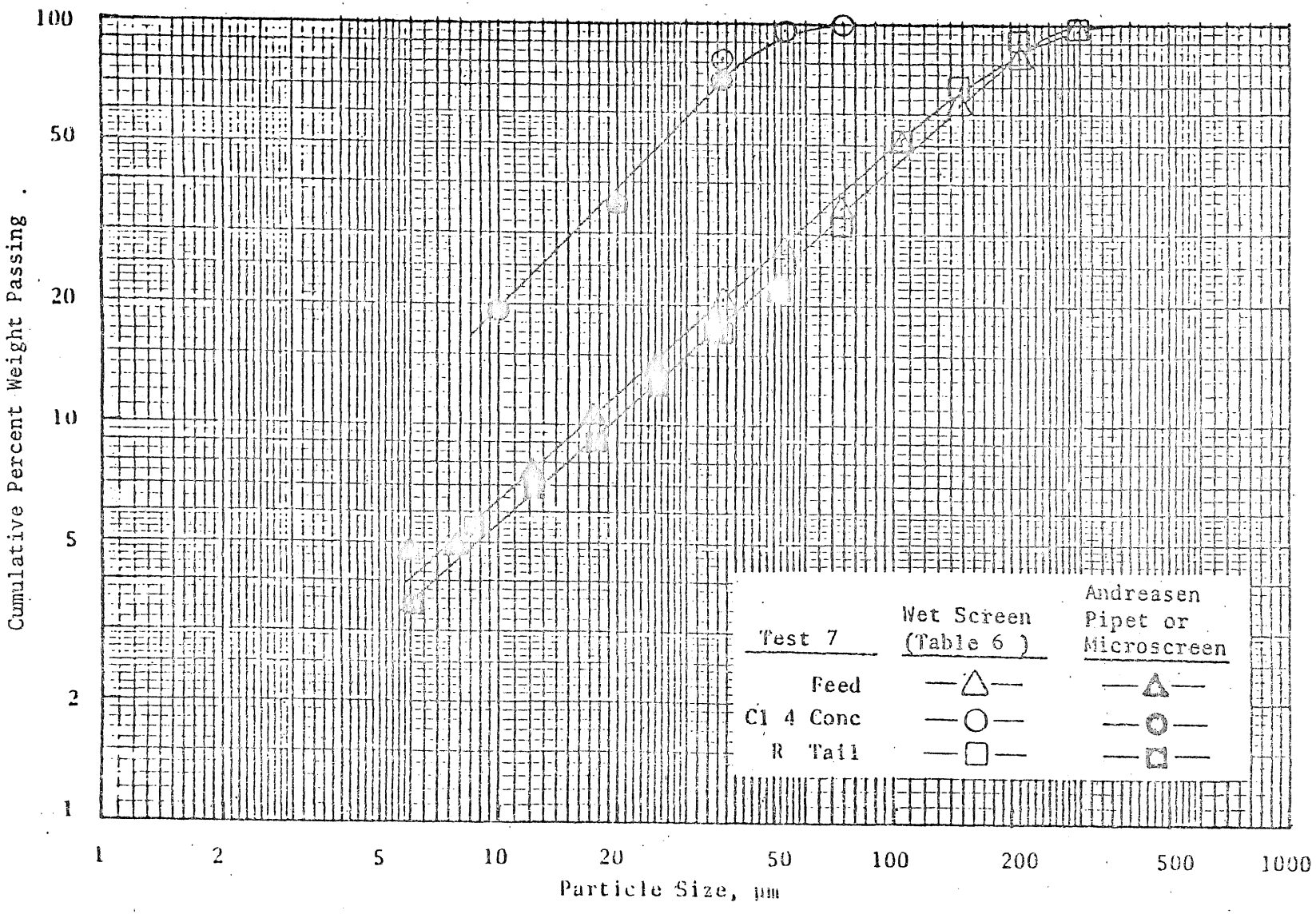


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF AX9001
(MINUS 65 MESH FOR FEED AND TAILING, MINUS 270 MESH FOR CONCENTRATE)

interest since the air-borne dusts are said to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200-mesh grind would have about 4 percent by weight of minus 5-μm particles. At a 65-mesh grind, however, minus 5 μm particles would be about 3 percent. The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

3.6 FLOTATION TESTS ON AX9002 SAMPLE

Sample Description

An AMAX shaft composite sample, labeled AX9002, weighing approximately 211 kilograms, was received on May 5, 1977, from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. This composite sample was reported to consist of the following individual round samples.

Sample Amount	Round	Depth	Assay
500 lb	198	1249	0.65 Cu (range 0.60-0.78)
(includes material	202		0.14 Ni
from 7 rounds)	203		0.98 S
	204		
	205		These are straight averages
	206		of assay values from seven
	207	1312	rounds.

The whole sample received was stage-crushed to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF AX9002 SAMPLE

Constituent	Percent
Copper (Cu)	0.60*
Nickel (Ni)	0.14**
Cobalt (Co)	0.014
Iron (Fe)	9.06
Sulfur (S)	1.00
Titanium dioxide (TiO_2)	1.25
Graphite carbon (CO	0.10

* Average of 5 analyses ranging 0.53-0.67% Cu
**Average of 5 analyses ranging 0.130-0.153% Ni

Grinding Characteristics

The grinding characteristics of the crude sample were investigated by grinding 1200-gram batches of minus 10-mesh feed in a stainless steel laboratory rod mill at 50 percent solids for various periods of time. The size distributions of the minus 10-mesh feed and of batches ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. The size distribution data of the ground batches are seen to follow straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.89. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In the figure the experimental points of IP9002 sample are also included for comparison. It is interesting to note that these two sets of points may be represented by a common straight line. The grinding characteristics of these two Duluth gabbro samples, therefore, may be regarded to be quite similar.

In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF AX9002 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50% SOLIDS)

Nominal Mesh-of-Grind	Grind Time Minutes	Size Modulus k, μm	80% passing μm
-10 mesh	0	-	1350
-48 mesh	15	280	220
-65 mesh	20	240	185
-100 mesh	30	175	140
-200 mesh	60	74	58

TABLE 2. SCREEN ANALYSIS OF AX9002 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 Mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	1.0	100.0	-	-	-	-	-	-	-	-
+14	23.6	99.0	-	-	-	-	-	-	-	-
+20	13.0	75.4	-	-	-	-	-	-	-	-
+28	24.8	62.4	-	-	-	-	-	-	-	-
+35	10.6	37.6	0.7	100.0	-	-	-	-	-	-
+48	7.1	27.0	6.2	99.3	2.4	100.0	-	-	-	-
+65	4.9	19.9	16.7	93.1	12.2	97.6	0.9	100.0	-	-
+100	4.2	15.0	20.6	76.4	24.2	85.4	8.9	99.1	-	-
+150	2.6	10.8	13.2	55.8	14.8	61.4	24.3	90.2	0.5	100.0
+200	2.0	8.2	11.6	42.6	12.3	46.6	20.0	65.9	5.1	99.5
+270	1.1	6.2	6.9	31.0	7.1	34.3	10.3	45.9	15.8	94.4
+325	0.8	5.1	4.3	24.1	4.2	27.2	6.0	35.6	13.3	78.6
+400	0.5	4.3	3.0	19.8	3.0	23.0	4.3	29.6	11.5	65.3
+500	1.4	3.8	6.0	16.8	6.6	20.0	8.8	25.3	20.5	53.8
-500	2.4	2.4	10.8	10.8	13.4	13.4	16.5	16.5	33.3	33.3

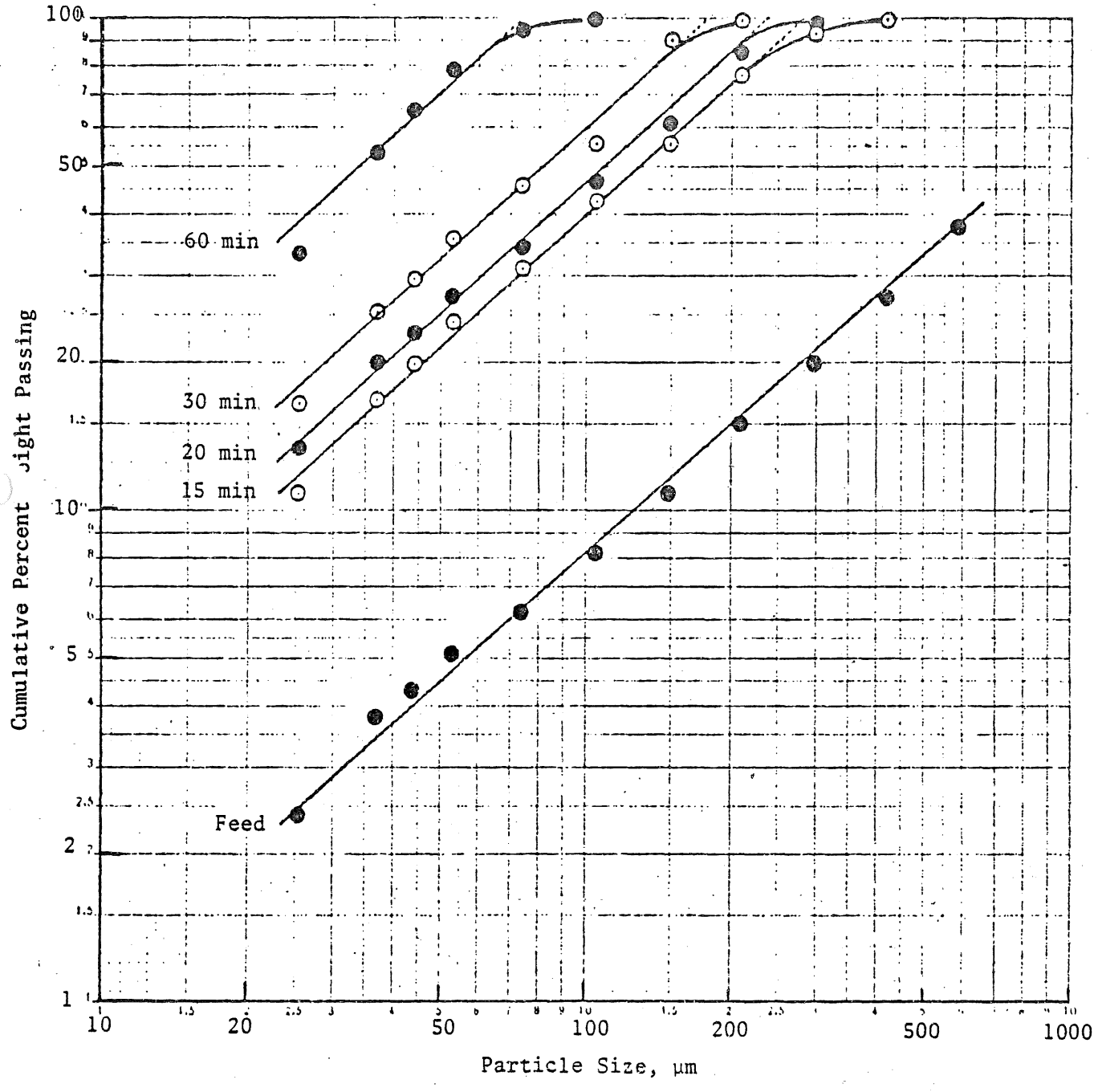


FIGURE 1. SIZE DISTRIBUTIONS OF AX9002 SAMPLE AS A FUNCTION OF GRINDING TIME

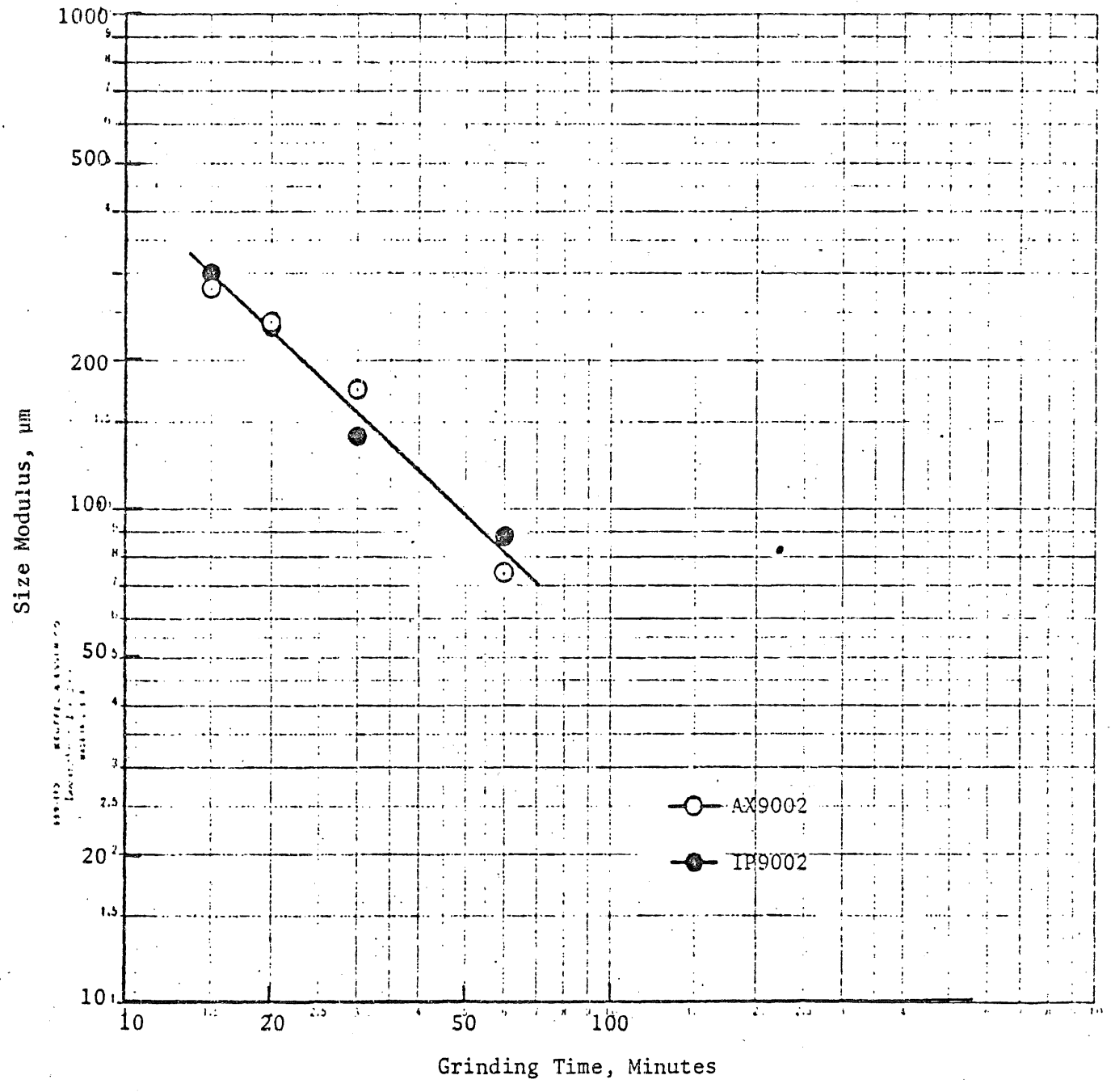


FIGURE 2. SIZE MODULI OF AX9002 AND IP9002 SAMPLES AS A FUNCTION OF GRINDING TIME

Preliminary Flotation Tests

Initially the effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed also at 5 minutes. The results of these flotation tests are given in Table 4.

The copper and nickel analysis data of rougher tailings (R Tail) would perhaps give the best indication of the effect of the mesh-of-grind. It is apparent in Table 4 that both copper and nickel losses to R Tails reach plateaus at 7 to 9 percent and about 23 percent, respectively, for minus 100- and 200-mesh grind samples. The losses of copper and nickel to R Tails tended to increase somewhat at 65 mesh and noticeably at 48 mesh. These observations indicate that the material should be ground to minus 65 mesh in minimizing the residual sulfide minerals in the rougher tailings. It is also noted that the concentrates after three cleaner stages analyzed in excess of 12 percent copper and approached 2.5 percent nickel. These observations are quite similar to the flotation behaviors of Inco's Spruce Road pit sample (IP9002).

During flotation sulfide minerals were observed to float very slowly, especially in the beginning. When the air valve was opened, a brittle froth layer of sulfide minerals that skimmed on the surface appeared for

TABLE 4. EFFECT OF MESH-OF-GRIND ON AX9002.
Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Cleaner - MIBC 0.06 lb/ton
Flotation Time: Rougher 5 min, Cleaner 5 min

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	3.33	13.01	2.56	64.41	48.66	3.33	13.01	2.56	64.41	48.66
		Cl 4 Tail	0.38	2.00	1.54	1.13	3.37	3.71	11.88	2.46	65.54	52.03
		Cl 3 Tail	0.67	1.43	0.86	1.43	3.31	4.38	10.28	2.22	66.97	55.34
		Cl 2 Tail	2.88	1.14	0.63	4.88	10.33	7.26	6.66	1.59	71.85	65.67
		Cl 1 Tail	6.31	0.40	0.145	3.75	5.25	13.57	3.75	0.92	75.60	70.92
		R Tail	86.43	0.19	0.059	24.40	29.08	100.00	0.67	0.18	100.00	100.00
2	65	Cl 4 Conc	4.37	11.30	2.09	81.62	59.91	4.37	11.30	2.09	81.62	59.91
		Cl 4 Tail	0.54	1.49	0.60	1.34	2.10	4.91	10.22	1.93	82.96	62.01
		Cl 3 Tail	1.42	0.91	0.36	2.13	3.35	6.33	8.13	1.57	85.09	65.36
		Cl 2 Tail	1.98	0.49	0.24	1.60	3.15	8.31	6.31	1.26	86.69	68.51
		Cl 1 Tail	8.72	0.20	0.093	2.88	5.32	17.03	3.18	0.66	89.57	73.83
		R Tail	82.97	0.076	0.048	10.43	26.17	100.00	0.61	0.15	100.00	100.00
3	100	Cl 4 Conc	4.22	13.99	2.43	86.61	60.93	4.22	13.99	2.43	86.61	60.93
		Cl 4 Tail	0.61	1.08	0.80	0.97	2.91	4.83	12.36	2.23	87.58	63.84
		Cl 3 Tail	1.05	0.92	0.65	1.42	4.04	5.88	10.32	1.94	89.00	67.88
		Cl 2 Tail	2.38	0.35	0.27	1.22	3.80	8.26	7.45	1.46	90.22	71.68
		Cl 1 Tail	9.82	0.17	0.094	2.45	5.46	18.08	3.49	0.72	92.67	77.14
		R Tail	81.92	0.061	0.047	7.33	22.86	100.00	0.68	0.17	100.00	100.00
4	200	Cl 4 Conc	4.26	14.06	2.57	87.42	63.52	4.26	14.06	2.57	87.42	63.52
		Cl 4 Tail	0.46	0.79	0.85	0.53	2.55	4.72	12.77	2.41	87.95	66.07
		Cl 3 Tail	1.00	0.37	0.39	0.54	2.26	5.22	10.60	2.06	88.49	68.33
		Cl 2 Tail	3.66	0.168	0.145	0.90	3.07	9.38	6.53	1.31	89.39	71.40
		Cl 1 Tail	13.90	0.081	0.073	1.65	5.92	23.28	2.68	0.57	91.04	77.32
		R Tail	76.72	0.080	0.051	8.96	22.68	100.00	0.69	0.17	100.00	100.00

a few minutes. While this layer of sulfide minerals was collected with a paddle, normal froths started to form after about 3 minutes and lasted throughout the remaining period in rougher flotation. This unusual froth characteristic was also observed in each of the four cleaner flotation steps. Such a behavior was independent of the mesh-of-grind.

In an attempt to improve the froth characteristics, the effects of the levels of the collector and the frother additions, of flotation time and of the use of kerosene were investigated, both on the one-stage grind flotation and the two-stage grind flotation processes. Initially, the frother was increased from 0.05 to 0.075 pound per ton to see if the froth characteristics could be improved (Table 5, Tests 6 and 7). In these tests the residual concentrations of MIBC were determined to see if there had been unusual abstraction of the collector and of the frother during the conditioning and flotation.. The residual concentrations of these reagents are seen to be in line with those of the IP9002 sample. The difference in their froth characteristics, therefore, could not be ascribed to unusual abstraction of either the collector or the frother by the AX9002 sample.

Increasing the rougher flotation time to 10 minutes resulted in a marked improvement in the nickel recovery (Test 8). Decreasing the amount of collector to 0.025 pound per ton resulted in decreased recoveries of both copper and nickel (Test 9). Though the extended flotation time could offset the detrimental effect of the unusual froth characteristics at the beginning, such a behavior could not be remedied by changing the amounts of reagents added.

TABLE 5. EFFECTS OF REAGENT LEVELS AND FLOTATION TIME (MINUS 200 MESH GRIND)

Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec	Residual Conc, ppm KAX	Residual Conc, ppm MIBC
						Test No. 6 Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 5 min, Cleaner 5 min						
Cl 2 Conc	2.57	21.42	1.01	88.51	15.85	2.57	21.42	1.01	87.91	15.85		
Cl 2 Tail	2.83	0.43	0.75	1.96	12.94	5.40	10.42	0.87	89.86	28.79		
Cl 1 Tail	16.30	0.14	0.38	3.67	37.77	21.70	2.70	0.50	93.50	66.56		
R Tail	78.30	.052	0.07	6.54	33.44	100.00	0.62	0.16	100.00	100.00	1.5 2.4	15.0[b] 11.9[a]
						Test No. 7 Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.075 lb/ton Cleaner - none Flotation Time: Rougher 5 min, Cleaner 5 min						
Cl 3 Conc	2.47	23.62	1.16	87.65	16.82	2.47	23.62	1.16	87.65	16.82		
Cl 3 Tail	.82	1.13	1.90	1.40	9.14	3.29	18.02	1.35	89.05	25.96		
Cl 2 Tail	3.43	0.47	1.18	2.42	23.74	6.72	9.06	1.26	91.47	49.70		
Cl 1 Tail	15.67	0.14	0.30	3.29	27.55	22.39	2.82	0.59	94.76	77.25		
R Tail	77.61	.045	0.05	5.24	22.75	100.00	0.67	0.17	100.00	100.00	1.6 3.1	20.7 16.6
						Test No. 8 Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton Cleaner - MIBC 0.20 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min						
Cl 4 Conc	4.18	14.36	2.68	92.00	60.97	4.18	14.36	2.68	92.00	60.97		
Cl 4 Tail	0.50	0.74	0.76	0.57	2.07	4.68	12.91	2.47	92.57	63.04		
Cl 3 Tail	1.03	0.38	0.34	.60	1.91	5.71	10.65	2.09	93.17	64.95		
Cl 2 Tail	3.26	.175	0.18	.89	3.21	8.97	6.84	1.40	94.06	68.16		
Cl 1 Tail	13.08	.070	.078	1.41	5.55	22.05	2.83	0.61	95.47	73.71		
R Tail	77.95	.038	.062	4.53	26.29	100.00	0.65	0.18	100.00	100.00		

(Continued)

TABLE 5 (CONTINUED)

Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec	Residual Conc, ppm KAX	Residual Conc, ppm MIBC
Test No. 9 Reagents: Rougher - KAX 0.025 lb/ton, MIBC 0.05 lb/ton Cleaner - MIBC 0.20 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min												
Cl 4 Conc	3.60	15.69	2.64	83.91	54.41	3.60	15.69	2.64	83.91	54.41		
Cl 4 Tail	0.35	0.95	0.87	.49	1.78	3.95	14.38	2.48	84.40	56.19		
Cl 3 Tail	0.96	0.54	0.50	.77	2.75	4.91	11.68	2.10	85.17	58.94		
Cl 2 Tail	3.14	0.23	0.24	1.07	4.30	8.05	7.21	1.37	86.24	63.24		
Cl 1 Tail	2.37	.086	.075	1.58	5.33	20.42	2.90	0.59	87.82	68.57		
R Tail	79.58	.103	.069	12.18	31.43	100.00	0.67	0.18	100.00	100.00		

[a]Before rougher flotation
[b]After rougher flotation

In an attempt to remedy the froth characteristics, a series of tests was made to investigate the use of kerosene in combination with the collector and/or the frother. The results are presented in Table 6. In Test 10 a combination of 0.07 pound of kerosene and 0.05 pound of MIBC per ton produced a copious froth from the beginning and a much shorter time (5 minutes) was needed to recover just as much copper and nickel in the rougher flotation as with a standard combination of KAX and MIBC in 10 minutes. Hence, the froth product collected for 5 minutes (rougher flotation) was set aside and the flotation continued for five more minutes without any additional reagents (scavenger flotation). The rougher concentrate was cleaned four times and the scavenger concentrate once. Although no collector was used, the grade of the fourth cleaner concentrate (Cl 4 Conc) and the recovery in the rougher-scavenger flotation were unexpectedly high. To compare the last test results with those obtained by using the standard reagent combination of 0.05 pound KAX and 0.05 pound MIBC per ton, the froth collection was divided into 3-minute periods (Test 13). It is apparent that the recovery of sulfide minerals was not as rapid as in Test 12. When KAX was used along with kerosene and MIBC, the brittle, skimming layer of sulfide minerals returned and good frothing occurred only after a few minutes as before (Test 11). The products were accidentally spilled during filtration and no test data were recorded.

Since a combination of kerosene and MIBC produced excellent results, Test 12 was carried out to see if an increase in the amount of kerosene to 0.11 pound per ton might further improve the froth characteristics. In this test the froth collection was again separated into 3-minute periods and only the rougher concentrate was cleaned three times.

TABLE 6. EFFECT OF KEROSENE ADDITION (MINUS 200-MESH GRIND)

Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
Test No. 10 Reagents: Kerosene 1b/ton, MIBC 0.05 1b/ton Flotation Time: Rougher 5 min, Scavenger 5 min, Cleaner 3 min										
Cl 4 Conc	3.66	16.24	2.86	86.92	59.32	3.66	16.24	2.86	86.92	59.32
Cl 4 Tail	0.27	1.86	0.20	.73	.28	3.93	15.26	2.67	87.65	59.60
Cl 3 Tail	.67	0.90	.86	.88	3.29	4.60	13.16	2.41	88.53	62.89
Cl 2 Tail	1.97	0.45	.34	1.30	3.80	6.57	9.35	1.79	89.83	66.69
Cl 1 Tail	14.54	.126	.107	2.68	8.84	21.11	3.00	0.63	92.51	75.53
Sc Cl 1 Conc	.46	.92	.38	.61	1.02	21.57	2.95	0.63	93.12	76.55
Sc Cl 1 Tail	5.43	.102	.091	.80	2.78	27.00	2.38	0.52	93.92	79.33
Sc Tail	73.00	.057	.050	6.08	20.67	100.00	0.68	0.18	100.00	100.00
Test No. 12 Reagents: Kerosene 0.11 1b/ton, MIBC 0.05 1b/ton Flotation Time: Rougher 3 min, Scavenger 3 min, Cleaner 3 min										
Cl 3 Conc	3.14	16.24	2.36	88.78	44.20	3.14	16.24	2.36	88.78	44.20
Cl 3 Tail	.38	1.37	1.23	0.91	2.80	3.52	14.63	2.24	89.69	47.00
Cl 2 Tail	1.15	0.51	0.65	1.03	4.48	4.67	11.16	1.85	90.72	51.48
Cl 1 Tail	11.37	0.19	.24	3.76	16.29	16.04	3.38	0.71	94.48	67.77
Sc 1 Froth	1.42	.122	.103	.30	.90	17.46	3.12	.66	94.78	68.67
Sc 2 Froth	1.59	.107	.065	.30	.60	19.05	2.87	.61	95.08	69.27
Sc 3 Froth	2.26	.066	.070	.26	.95	21.31	2.57	.55	95.34	70.22
Sc 4 Froth	1.92	.075	.068	.24	.78	23.23	2.36	.51	95.58	71.00
Sc 5 Froth	1.69	.084	.074	.24	.78	24.92	2.21	.48	95.82	71.78
Sc 5 Tail	75.08	.032	.063	4.18	28.22	100.00	0.57	.17	100.00	100.00

(Continued)

TABLE 6 (CONTINUED)

Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
	Test No. 13	Reagents: KAX .05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 3 min, Scavenger 3 min								
R Conc	8.69	6.45	0.99	87.96	46.54	8.69	6.45	0.99	87.96	46.54
Sc 1 Froth	4.76	.56	.90	4.19	23.16	13.45	4.37	.96	92.15	69.70
Sc 2 Froth	4.81	.192	.132	1.44	3.46	18.26	3.27	.74	93.59	73.16
Sc 3 Froth	2.51	.095	.100	.38	1.35	20.77	2.88	.66	93.97	74.51
Sc 4 Froth	2.42	.080	.097	.30	1.30	23.19	2.59	.60	94.27	75.81
Sc 5 Froth	2.34	.064	.095	.24	1.19	25.53	2.36	.56	94.51	77.00
Sc 5 Tail	74.47	.047	.057	5.49	23.00	100.00	0.63	.19	100.00	100.00
	Test No. 14	Reagents: Rougher - Kerosene 0.05 lb/ton, MIBC 0.05 lb/ton Scavenger - Copper Sulfate 0.5 lb/ton, KAX 0.025 lb/ton Flotation Time: Rougher 3 min, Scavenger 3 min (pH 5.6)								
R Conc	17.29	3.71	0.84	95.76	77.03	17.29	3.71	0.84	95.76	77.03
Sc 1 Froth	2.84	.167	.132	.70	2.02	20.13	3.21	.74	96.46	79.05
Sc 2 Froth	2.06	.083	.100	.25	1.11	22.19	2.92	.68	96.71	80.16
Sc 3 Froth	2.82	.069	.080	.30	1.22	25.01	2.60	.61	97.01	81.38
Sc 4 Froth	2.09	.063	.076	.19	.85	27.10	2.40	.57	97.20	82.23
Sc 5 Froth	2.34	.078	.085	.27	1.06	29.44	2.22	.53	97.47	83.29
Sc 5 Tail	70.56	.024	.044	2.53	16.71	100.00	0.67	.19	100.00	100.00
	Test No. 16	Reagents: MIBC 0.05 lb/ton (only) Flotation Time: Rougher 5 min, Cleaner 3 min								
Cl 4 Conc	3.51	17.20	2.85	89.29	56.50	3.51	17.20	2.85	89.29	56.50
Cl 4 Tail	0.27	2.01	1.84	.80	2.83	3.78	16.11	2.78	90.09	59.33
Cl 3 Tail	0.64	0.90	1.00	.86	3.62	4.42	13.91	2.52	90.95	62.95
Cl 2 Tail	2.26	0.41	0.38	1.38	4.86	6.68	9.34	1.80	92.33	67.81
Cl 1 Tail	14.05	.127	.095	2.63	7.57	20.73	3.10	.64	94.96	75.38
R Tail	79.27	.043	.055	5.04	24.62	100.00	0.68	.18	100.00	100.00

Thus far, the flotation tailings have analyzed in excess of 0.05 percent both in copper and nickel. To investigate if the contents of these metals could be lowered any further, a rougher tailing, obtained with 0.05 pound each of kerosene and MIBC per ton, was acidified with carbon dioxide to pH 5.8 and activated with 0.5 pound of copper sulfate per ton (Test 14). The activated rougher tailing pulp was then scavenged by using 0.025 pound of KAX per ton. After five scavenger operations of 3 minutes each, the tailing analyzed 0.024 percent copper and 0.044 percent nickel, the lowest ever recorded on any Duluth gabbro samples tested so far. The grades of the scavenger froths suggest, however, that the sulfides in the flotation tailings had been perhaps insufficiently liberated.

In this series of flotation tests the beneficial effect of kerosene was demonstrated, but it is well known that kerosene is not a collector. To provide a reference point, Test 16 was carried out using only 0.05 pound of MIBC per ton. Surprisingly, excellent froth characteristics as well as metallurgical results were obtained with only the frother. It is puzzling that the use of KAX with or without kerosene adversely affected the froth characteristics. The graphitic carbon content of the present sample is only 0.1 percent, so it is difficult to perceive that this small amount of graphite had anything to do with the unusual froth characteristics. To check if there were unusually high concentrations of copper and/or nickel ions that might precipitate the collector, a flotation pulp sample taken prior to the addition of the collector was centrifuged and analyzed. A similar test was made on a flotation pulp of the IP9002 sample and the results are listed in Table 7. These concentrations are in agreement with the analysis of the feed water in Table 18 and furthermore the table does

not show the presence of any heavy metal ions in appreciable concentrations. It may be concluded, therefore, that any heavy metal ions in pulp solutions could not have been responsible for the unusual froth characteristics.

TABLE 7. COPPER AND NICKEL CONTENTS IN FLOTATION PULP SOLUTIONS PRIOR TO KAX ADDITION

Sample	Cu, ppm	Ni, ppm
AX9002	0	0.05
IP9002	0	0.02

A two-stage grind flotation procedure was tested by performing rougher-cleaner flotation on three 1200-gram samples ground to minus 65 mesh and combining the three cleaner concentrates and regrinding them to minus 270 mesh. The preliminary flotation test results are given in Table 8. The time required for regrinding was estimated by first filtering and weighing the combined cleaner concentrates, then grinding the concentrate in a laboratory rod mill at 50 percent solids for 10 minutes, and screening the ground product on a 270-mesh screen. By repeating the grinding and screening procedure, it was estimated that a total of 16 minutes was required to grind approximately 290 grams (dry basis) of the combined cleaner concentrate to minus 270 mesh.

In the cleaning of the reground concentrates the same unusual froth characteristics as previously mentioned were observed during the first few minutes of flotation. In Test 5 an additional 0.05 pound of KAX per ton was used in the first cleaner flotation along with 0.03 pound of MIBC per ton, but the unusual froth characteristics could not be corrected. It is apparent that the grades of reground cleaner concentrates were

TABLE 8. TWO-STAGE FLOTATION TESTS - ROUGHER FLOTATION AT MINUS 65 MESH, REGRINDING TO MINUS 270 MESH AND REFLOTATION

Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
Test No. 5 Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton; 1st Cleaner - KAX 0.05 lb/ton, MIBC 0.03 lb/ton. Flotation Time: Rougher 5 min, Regr Cleaner 5 min										
Regr Cl 4 Conc	2.57	20.03	3.48	85.94	50.68	2.57	20.03	3.48	85.94	50.68
Regr Cl 4 Tail	.17	1.21	3.04	.35	2.95	2.74	18.87	3.45	86.29	53.63
Regr Cl 3 Tail	.31	0.78	1.42	.40	2.49	3.05	17.03	3.25	86.69	56.12
Regr Cl 2 Tail	1.02	.32	.45	.55	2.61	4.07	12.84	2.55	87.24	58.73
Regr Cl 1 Tail	4.02	.155	.14	1.04	3.18	8.09	6.54	1.35	88.28	61.91
Cl Tail	7.34	.15	.11	1.85	4.54	15.43	3.50	0.76	90.12	66.45
R Tail	84.57	.07	.07	9.88	33.55	100.00	0.60	0.18	100.00	100.00
Test No. 17 Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton; Regr Cleaner - MIBC 0.075 lb/ton. Flotation Time: Rougher 10 min, Regr Cleaner 5 min										
Regr Cl 4 Conc	2.23	22.50	2.38	81.44	32.48	2.23	22.50	2.38	81.44	32.48
Regr Cl 4 Tail	.08	3.38	2.76	.44	1.35	2.31	21.84	2.39	81.88	33.83
Regr Cl 3 Tail	.36	2.55	4.90	1.49	10.77	2.67	19.24	2.73	83.37	44.60
Regr Cl 2 Tail	.99	1.04	2.15	1.67	13.03	3.66	14.32	2.57	85.04	57.63
Regr Cl 1 Tail	3.07	0.40	.64	2.00	12.05	6.73	7.97	1.69	87.04	69.68
Cl Tail	6.75	.183	.120	2.01	4.95	13.48	4.07	0.91	89.05	74.63
R Tail	86.52	.078	.048	10.95	25.37	100.00	0.62	0.16	100.00	100.00

notably higher than those of the one-stage grind flotation tests at minus 200 mesh. In Test 17 the cleaner flotation after regrinding was performed with only an MIBC addition. It is apparent in the table that KAX was not necessary in the cleaning step.

To investigate if KAX adversely affected the froth characteristics on minus 65-mesh samples as mentioned previously, a few exploratory tests were made and the results are presented in Table 9. In these tests the froth product was collected in separate fractions as a function of time in an attempt to show the unusual froth characteristics in metallurgical results. In Test 18 only the frother was used (MIBC, 0.05 pound per ton). The froth characteristics remained normal throughout the flotation time of 20 minutes. The recoveries of copper and nickel amounted to only 76 and 61 percent, respectively. Test 19 was carried out by collecting the froth in the first 6 minutes with the frother only and then the remaining pulp was floated with 0.025 pound each of KAX and MIBC per ton for an additional 14 minutes. The froth characteristics remained normal and the recoveries of copper and nickel increased to 89 and 76 percent, respectively. In Test 20 the standard reagent combination of 0.05 pound each of KAX and MIBC per ton was used. The unusual froth characteristics appeared in the first 5 minutes, but the froth improved gradually thereafter. Despite this frothing behavior the recoveries of copper and nickel increased to 90 and 74 percent, respectively. Again it was observed that the use of KAX adversely affected the initial froth characteristics, but was beneficial in improving the overall metallurgical results if the flotation time was extended to offset the initial slow-floating froth.

TABLE 9. EFFECT OF KAX ON FLOTATION OF MINUS 65-MESH SAMPLES

Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
Test No. 18 Reagents: MIBC 0.05 lb/ton (only)										
0-3' Froth	6.53	7.42	1.63	72.62	57.64	6.53	7.42	1.63	72.62	57.64
3-6' Froth	1.26	0.67	.168	1.26	1.14	7.79	6.33	1.39	73.88	58.78
6-9' Froth	1.52	0.36	.105	.82	.87	9.31	5.35	1.18	74.70	59.65
9-12' Froth	1.05	.218	.091	.35	.54	10.36	4.83	1.07	75.05	60.19
12-15' Froth	1.05	.165	.087	.26	.49	11.41	4.40	0.98	75.31	60.68
15-20' Froth	1.55	.132	.080	.32	.65	12.96	3.89	0.87	75.63	61.33
Tails	87.04	.187	.082	24.37	38.67	100.00	0.68	0.19	100.00	100.00
Test No. 19 Reagents: First 6 min MIBC 0.05 lb/ton (only) Beyond 6 min KAX 0.025 lb/ton, MIBC 0.025 lb/ton										
0-3' Froth	7.93	5.96	1.30	73.04	62.49	7.93	5.96	1.30	73.04	62.49
3-6' Froth	1.74	0.40	.142	1.08	1.52	9.67	4.96	1.09	74.12	64.01
6-9' Froth	3.84	2.15	0.46	12.76	10.73	13.51	4.16	0.92	86.88	74.74
9-12' Froth	1.00	0.74	.095	1.14	.61	14.51	3.93	.86	88.02	75.35
12-15' Froth	0.85	0.25	.072	.32	.36	15.36	3.72	.81	88.34	75.71
15-20' Froth	1.50	0.21	.065	.49	.61	16.86	3.41	0.75	88.83	76.32
Tails	83.14	.087	.047	11.17	23.68	100.00	0.65	0.17	100.00	100.00
Test No. 20 Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton										
0-3' Froth	7.76	7.00	1.48	84.82	64.49	7.76	7.00	1.48	84.82	64.49
3-6' Froth	3.11	0.85	0.40	4.12	6.97	10.87	5.24	1.17	88.89	71.46
6-9' Froth	1.35	0.34	.117	.72	.90	12.22	4.70	1.05	89.66	72.36
9-12' Froth	1.24	0.14	.080	.27	.56	13.46	4.28	0.96	89.93	72.92
12-15' Froth	1.94	.091	.074	.28	.79	15.40	3.75	0.85	90.21	73.71
15-20' Froth	1.80	.079	.071	.22	.73	17.20	3.37	0.77	90.43	74.44
Tails	82.80	.074	.055	9.57	25.56	100.00	0.64	0.18	100.00	100.00

The exact cause of the unusual froth characteristics at the beginning of flotation could not be determined in this preliminary series of flotation tests and further investigation is needed to resolve the cause and to prescribe the remedy for this difficulty. Nevertheless, this particular problem could be overcome at least in the present investigation by extending the flotation time in the standardized procedures.

Standardized Flotation Test Results

The results of flotation tests according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 10 and the size distributions of their flotation feed and products in Table 11. Though the present sample showed unusual froth characteristics as mentioned in the previous section, the metallurgical results obtained by the standardized flotation procedures were satisfactory. The recoveries of copper, nickel and sulfur in the rougher flotation were 93.95%, 77.50%, and 96.12%, respectively, at 200 mesh (one-stage grind flotation), and were 90.78%, 76.50%, and 92.85%, respectively, at 65 mesh (two-stage grind flotation). The flotation concentrate could be upgraded to 13.77 percent copper and 2.48 percent nickel in the one-stage grind flotation after three cleanings, whereas in the two-stage grind flotation the concentrate was upgraded to 14.86 percent copper and 2.66 percent nickel after one cleaning following regrinding. The sum of the copper, nickel, cobalt, iron and sulfur may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides.

TABLE 10(a). STANDARDIZED FLOTATION TEST RESULTS ON AX9002

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 15 Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 10 min Pulp Temperature: 28°C Rougher pH: 9.3							
Cl 4 Conc	3.68	15.56	2.75	0.074	27.70	21.48	0.48
Cl 4 Tail	0.50	0.60	0.52	0.020	12.64	2.60	-
Cl 3 Tail	1.52	0.37	0.31	0.016	12.08	1.95	-
Cl 2 Tail	4.34	0.138	0.134	0.009	10.80	0.66	-
Cl 1 Tail	14.37	0.085	0.075	0.009	10.76	0.37	-
R Tail	75.59	0.051	0.048	0.008	10.45	0.061	-
Flotation Feed	100.00	0.63	0.153				0.104
Test No. 21 Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 29°C Rougher pH: 9.2							
Regr Cl 4 Conc	2.48	22.62	3.30	0.13	33.26	30.53	0.55
Regr Cl 4 Tail	0.17	1.98	5.06	0.205	20.03	10.45	
Regr Cl 3 Tail	0.29	1.10	1.92	0.082	15.75	5.36	
Regr Cl 2 Tail	0.92	0.65	0.73	0.040	13.20	3.20	
Regr Cl 1 Tail	2.78	0.34	0.24	0.020	11.92	2.07	
Cl Tail	8.51	0.41	0.171	0.016	11.15	1.35	
R Tail	84.85	0.074	0.045	0.013	10.87	0.09	
Flotation Feed	100.00	0.67	0.151	0.020	10.90	0.99	

TABLE 10(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON AX9002

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No.15 One-stage Grind Flotation																	
Cleaner 4	3.68	15.56	2.75	0.074	27.70	21.48	89.75	62.70	25.86	9.12	85.67	96.32	0.068	0.062	0.008	10.55	0.18
Cleaner 3	4.18	13.77	2.48	0.067	25.89	19.22	90.22	64.31	26.82	9.68	86.76	95.82	0.065	0.060	0.008	10.54	0.16
Cleaner 2	5.70	10.20	1.90	0.053	22.21	14.62	91.10	67.22	28.74	11.33	89.25	94.30	0.060	0.056	0.008	10.51	0.14
Cleaner 1	10.04	5.85	1.14	0.030	17.27	8.58	92.04	70.81	29.12	15.52	91.65	89.96	0.056	0.052	0.008	10.50	0.11
Rougher	24.41	2.46	0.51	0.018	13.44	3.75	93.95	77.50	41.57	29.35	96.12	75.59	0.051	0.048	0.008	10.45	0.061
Test No.16 Two-stage Grind Flotation																	
Regr Cleaner 4	2.48	22.62	3.30	0.130	33.26	30.53	82.40	50.46	18.50	7.12	70.84	97.52	0.123	0.082	0.015	10.97	0.32
Regr Cleaner 3	2.65	21.30	3.41	0.139	32.08	29.24	82.90	55.77	21.39	7.38	72.51	97.35	0.120	0.074	0.014	10.96	0.30
Regr Cleaner 2	2.94	19.31	3.27	0.133	30.61	26.88	83.37	59.23	22.55	7.81	73.96	97.06	0.117	0.068	0.014	10.94	0.29
Regr Cleaner 1	3.86	14.86	2.66	0.111	26.43	21.24	84.25	63.36	24.86	8.85	76.71	96.14	0.111	0.062	0.014	10.92	0.26
Cleaner	6.64	8.78	1.65	0.074	20.33	13.21	85.65	67.49	28.33	11.72	82.10	93.36	0.105	0.056	0.013	10.89	0.21
Rougher	15.15	4.08	0.82	0.042	15.18	6.55	90.78	76.50	36.42	19.97	92.85	84.85	0.074	0.045	0.013	10.87	0.09

TABLE 11. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF AX9002

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 15 - One-stage Grind Flotation (Minus 200 mesh)		
+150	1.70	0.63	1.35
+200	11.98	1.27	9.14
+270	28.42	8.86	28.11
+400	15.16	18.35	20.43
-400	42.74	70.89	40.97
	(b) Test 21 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	1.32	-	-
+65	10.29	-	3.42
+100	25.60	-	19.93
+150	22.96	-	31.89
+200	11.03	-	14.81
+270	3.54	1.75	7.51
+400	8.22	17.02	6.95
-400	17.04	81.23	15.49

*Cl 4 Conc and Regr Cl 4 Conc, respectively

The third cleaner concentrate (Cl 3 Conc) in the one-stage grind flotation would then have 38.6 percent gangue and the regrind first cleaner concentrate (Regr Cl 1 Conc) in the two-stage grind flotation would have 34.7 percent gangue.

The effectiveness in upgrading the flotation concentrates after regrinding might be related to the degree of liberation of the sulfide minerals and to the dependence of flotation rates on the size of sulfide minerals. In general, the finer the sulfide mineral, the faster the flotation. But in the near colloidal range, say minus 5 μm, decreased probability of collision between air bubbles and particles would lead to decreased flotation recovery. Table 12 gives the results of chemical analyses made on microscreened size fractions of an R Tail sample and it is readily apparent that the copper and sulfur contents in the minus 10-μm fraction are notably high.

TABLE 12. CHEMICAL ANALYSES OF SIZE FRACTIONS IN THE SUBSIEVE RANGE OF R TAIL SAMPLE (TEST 15)

Size, mesh	% Wt	% S	% Cu	% Ni	% Co	% Fe
+37	59.65	0.05	0.035	0.041	0.013	10.78
+20	20.56	0.03	0.043	0.040	0.015	11.04
+10	9.69	0.06	*	*	*	*
-10	10.10	0.19	0.36	0.075	0.012	11.55
Composite	100.00	0.061	(0.051)**	(0.048)**	(0.008)**	(10.45)**

* Insufficient sample for chemical analyses
**From Table 6

The flotation recoveries of nickel and especially cobalt are low, but apparently they cannot be attributed to the failures of the fine nickel- and cobalt-bearing sulfide minerals to flotation so evident in Table 12. A detailed mineralogical investigation on this point is warranted. A Davis magnetic tube test was performed on a Cl 4 Conc sample to explore the feasibility of a copper-nickel separation, but the magnetic concentrate amounted to only 1.58 percent by weight. Hence, chemical analyses on the magnetic separation products were not made. Evidently, the pyrrhotite in the present sample is the nonmagnetic variety.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, and R Tail samples in the one-stage grind flotation test and the Feed, Regr Cl 4 Conc, Cl Tail, and R Tail samples in the two-stage grind flotation test were analyzed by Barringer Research Ltd. The results are given in Tables 13 and 14. In these tables it is seen that the concentration of such trace elements as zinc, silver, and lead notably increased. The amounts of cadmium and mercury in the cleaner concentrates increased to some extent. These increases are perhaps to be expected since these elements are closely associated with sulfide minerals. The analyses of phosphorus in all the samples were unexpectedly high. Hence a wet chemical analysis was performed on a concentrate. It showed that the phosphorus value reported by Barringer might be in error. The silicon analyses in Table 14 appear to be unreasonably low since the feed and the tailing samples were essentially silicates. Furthermore, the Barringer data of the Cleaner Tailing and the Rougher Tailing in Table 14 appear to be transposed.

TABLE 13. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9002 (TEST 15 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Cl 4 Conc (-200 mesh)		R Tail (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.55		2.70		8.61	
Be	nd		nd		nd	
Ca	4.96		1.69		5.00	
Cu	0.575	0.67	14.50	15.56	0.0161	0.051
Fe	9.16	10.90	25.80	27.70	8.78	10.45
Mg	3.92		1.86		3.75	
Mn	0.120		0.0434		0.1230	
P	0.216		3.40	0.020**	0.126	
Ba	0.0182		0.0048		0.0176	
As	nd		nd		nd	
Sr	0.0244		0.00767		0.0263	
Zr	0.0110		0.0058		0.0140	
Ti	1.18		0.117		1.29	
V	0.0176		0.0113		0.0183	
Zn	0.0174		0.151	0.071	0.0116	
K	0.27		0.0536		0.23	
Na	2.0		0.642		2.17	
Cd	0.0004		0.0008		0.0051	
Cr	0.0293		0.00518	0.019	0.0245	
Co	0.0109	0.020	0.0898	0.074	0.0078	0.008
Ag	nd		0.0041		nd	
Mo	0.0007		0.0012		0.0003	
Ni	0.113	0.151	2.41	2.75	0.0287	0.048
Pb	0.0062		0.0143		0.0017	
Hg***	0.0000090		0.0000140		0.0000070	

(Continued)

TABLE 13 - CONTINUED (AX9002)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
F^-	5.7****					
Cl^-	653					
NO_2^-	52					
$PO_4^{\equiv}$	<40					
Br^-	<16					
NO_3^-	160					
$SO_4^{\equiv}$	419					

* Conventional AA analyses
** Wet chemical analyses
*** 0.0000001% = 1 ppb
****All the anion analysis results in ppm

TABLE 14. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9002 (TEST 21 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Regr Cl 4 Conc (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	9.43		0.759		9.33		9.50	
B	0.0157		nd		0.0766		0.129	
Be	nd		nd		nd		nd	
Ca	5.69		0.47		5.63		5.69	
Cu	0.592	0.67	22.30	22.62	0.0362	0.41	0.40	0.074
Fe	10.30	10.90	34.30	33.26	10.00	11.15	10.20	10.87
Mg	6.09		1.10		6.02		5.95	
Mn	0.12		0.0175		0.128		0.111	
P	0.248		5.69		0.145		0.222	
Ba	0.0283		0.0022		0.0597		0.0868	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
As	nd		nd		nd		nd	
Si	0.244		0.0287		0.773		1.23	
Sr	0.0272		0.0021		0.0276		0.0272	
Zr	0.0046		0.0010		0.0081		0.0064	
Ti	1.24		0.0524		1.41		0.80	
V	0.0214		0.0130		0.0223		0.0196	
Zn	0.0164		0.228		0.0105		0.0156	
Th	0.0014		0.0010		0.0014		0.0014	
K	0.30		0.13		0.32		0.38	
Na	2.17		0.20		2.30		2.18	
Cd	nd		0.0020		nd		nd	
Cr	0.0171		0.00292		0.0138		0.0427	
Co	0.0137	0.020	0.136	0.13	0.0097	0.016	0.0132	0.013
Ag	0.00055		0.00568		0.00041		0.00068	
Mo	nd		nd		nd		nd	
Ni	0.134	0.151	3.29	3.30	0.0334	0.171	0.143	0.045
Pb	nd		0.0090		nd		nd	

* Conventional AA analyses

To relate the flotation behaviors to the liberation characteristics of sulfide minerals the flotation feed, concentrate and tailing samples were screened into size fractions and the mineralogical composition of each fraction was determined by examining it first under transmitted light for silicate minerals and then under reflected light for opaque minerals. The results on the sized fractions from the one-stage grind flotation are shown in Tables 15(a) and (b), and on those from the two-stage grind flotation in Tables 16(a) and (b).

In these tables it is apparent that silicate minerals consist mainly of feldspar, pyroxene, biotite, olivine and others, including chlorite and amphibole, all of which were well-liberated from each other both at 65 and 200 mesh grind. There appeared to be some tendency for opaque minerals to break down preferentially to finer sizes and for pyroxene and biotite to resist grinding to finer sizes. Preferential grinding of sulfide minerals was well illustrated in the size distributions of concentrates in Table 11(a). It is interesting to note that, although at a 65-mesh grind, biotite was more or less evenly distributed over all size fractions, nearly a half of the plus 150-mesh fraction was biotite at a 200-mesh grind. Those particles locked with opaque minerals in the feed were seen to consist of roughly equal numbers of sulfide/gangue and ilmenite or magnetite/gangue particles over all the size fractions. In R Tails, however, those particles locked with sulfides decreased as the particle size became finer.

A closer examination of the relevant columns in Tables 15(b) and 16(b) shows that coarse locked particles consist mainly of Cp-Cb/gangue particles and very little Po-Pn/gangue particles, and that fine locked

TABLE 15(a). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF ONE-STAGE GRIND FLOTATION (TEST 15) ON AX9002 UNDER TRANSMITTED LIGHT

Size, mesh	% Wt	Free Particles						Locked Particles		
		Opaques	Olivine	Pyroxene	Feldspar	Biotite	Others*	Op/Olivine Pyroxene	Op/Feld	Op/Others*
					(a) Feed					
150	1.70	2.2	9.6	20.2	13.8	48.7	4.5	0	0	1.0
200	11.98	0.6	11.6	35.2	23.6	10.4	14.5	2.8	0	1.3
270	28.42	6.3	14.6	22.3	41.2	4.7	9.6	0.3	0.7	0.3
400	15.16	13.3	11.3	9.3	39.2	9.6	8.6	3.3	2.7	2.7
-400	42.74	- - - - - - -	not determined	- - - - - - -				- -	not determined	- -
					(b) R Tail					
150	1.35	1.3	5.0	29.2	5.0	38.9	13.5	1.7	0	5.4
200	9.14	1.8	10.9	31.1	23.0	14.2	16.3	0.9	0	1.8
270	28.11	2.1	9.3	30.6	50.1	2.8	3.4	0.6	0	0
400	20.43	5.4	12.1	19.2	40.3	8.6	13.1	1.0	0.3	0
-400	40.97	- - - - - - -	not determined	- - - - - - -				- -	not determined	- -
					(c) Cl 4 Conc					
150	0.63	25.2	2.0	30.7	1.0	17.3	13.4	4.5	0	5.9
200	1.27	30.4	5.5	23.9	6.1	3.4	7.9	18.8	1.0	3.0
270	8.86	47.8	2.4	2.9	4.5	1.3	0.6	15.6	23.1	1.8
400	18.35	34.2	3.0	23.2	6.0	9.5	13.1	3.6	7.4	0
-400	70.89	- - - - - - -	not determined	- - - - - - -				- -	not determined	- -

*Others: chlorite, amphibole, apatite

TABLE 15(b). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF ONE-STAGE GRIND FLOTATION (TEST 15) ON AX9002 UNDER REFLECTED LIGHT

Size, mesh	Free Particles			Locked Particles				
	Po-Pn	Cp-Cb	Ilm/Mag	Po-Pn/ Gangue	Cp-Cb/ Gangue	Ilmenite/ Gangue	Magnetite Gangue	Po-Pn/ Cp-Cb
				(a) Feed				
150	0	tr	100	20	50	tr	30	0
200	0	tr	100	10	40	10	40	0
270	0	tr	100	tr	tr	20	80	0
400	tr	40	60	10	40	20	30	0
-400	tr	50	50	tr	40	20	40	0
				(b) R Tail				
150	tr	tr	100	tr	50	tr	50	tr
200	tr	tr	95	tr	90	tr	10	tr
270	tr	tr	95	tr	40	10	50	tr
400	tr	tr	95	tr	20	15	65	0
-400	tr	tr	95	tr	tr	10	90	0
				(c) Cl 4 Conc				
150	0	tr	100	tr	40	tr	60	0
200	tr	95	tr	tr	90	tr	10	tr
270	tr	95	tr	tr	90	tr	10	tr
400	tr	100	tr	tr	90	tr	10	tr
-400	tr	80	tr	tr	90	tr	10	tr

tr: trace (less than ~5%)

Cp: chalcopyrite
Cb: cubanite
Pn: pentlandite
Po: pyrrhotite
Ilm: ilmenite
Mag: magnetite

TABLE 16(a). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF TWO-STAGE GRIND FLOTATION (TEST 21) ON AX9002 UNDER TRANSMITTED LIGHT

Size, mesh	% Wt	Free Particles						Locked Particles		
		Opaques	Olivine	Pyroxene	Feldspar	Biotite	Others*	Op/Olivine Pyroxene	Op/Feld	Op/Others*
					(a) Feed					
48	1.32	0.2	20.3	24.1	45.3	5.1	2.0	1.8	1.2	0.0
65	10.29	1.2	19.4	23.7	42.3	3.1	2.1	2.9	5.2	0.1
100	25.60	4.3	31.5	17.3	38.2	1.1	2.3	2.6	2.3	0.4
150	22.96	6.3	38.6	5.9	42.2	2.1	0.9	0.6	1.5	0.0
200	11.03	6.3	23.6	10.7	53.2	3.2	2.0	0.9	0.1	0.0
270	3.54	11.7	13.4	8.0	48.1	5.2	4.7	5.6	3.3	0.0
400	8.22	12.4	19.9	7.3	42.4	5.9	4.8	2.7	4.6	0.0
-400	17.04	14.3	12.2	8.8	55.1	5.4	4.1	0.0	0.0	0.0
					(b) R Tail					
65	3.42	3.7	22.5	25.8	36.3	5.4	0.4	2.4	2.2	1.3
100	19.93	6.3	27.5	26.0	30.8	3.1	2.2	1.4	2.4	0.3
150	31.89	10.9	29.4	9.6	44.3	1.3	2.2	0.6	1.7	0.0
200	14.81	4.5	26.2	10.2	44.9	1.6	8.9	2.4	1.3	0.0
270	7.51	12.5	16.6	4.8	48.4	6.2	8.6	2.0	0.9	0.0
400	6.95	8.3	21.9	6.9	48.3	5.2	8.8	0.5	0.1	0.0
-400	15.49	5.6	18.9	4.9	64.3	2.8	3.5	0.0	0.0	0.0
					(c) C1 4 Conc					
270	1.75	- - - - - - - - - - - - not determined - - - - - - - - - - - -						- - - - not determined - -		
400	17.02	62.0	1.1	2.1	5.1	1.5	2.6	5.7	17.4	2.5
-400	81.23	90.1	0.1	0.8	5.1	0.0	3.8	0.0	0.1	0.0

*Others: chlorite, amphibole, apatite

TABLE 16(b). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF TWO-STAGE GRIND FLOTATION (TEST 21) ON AX9002 UNDER REFLECTED LIGHT

Size, mesh	Free Particles			Locked Particles			
	Po-Pn	Cp-Cb	Ilm/Mag	Po-Pn/ Gangue	Cp-Cb/ Gangue	Ilm/Mag Gangue	Po-Pn/ Cp-Cb
			(a) Feed				
48	0	tr	100	0	80	20	0
65	0	0	100	0	80	20	0
100	0	tr	100	0	90	10	0
150	0	30	70	tr	80	20	0
200	tr	40	60	tr	30	70	0
270	tr	60	40	tr	40	60	0
400	tr	70	30	tr	50	50	0
-400	tr	80	20	0	70	30	0
			(b) R Tail				
65	0	0	100	0	100	tr	0
100	0	0	100	0	90	10	0
150	tr	tr	100	0	70	30	0
200	0	0	100	tr	50	50	0
270	0	0	100	tr	40	60	0
400	tr	10	90	tr	50	50	0
-400	10	tr	90	10	tr	90	0
			(c) Cl 4 Conc				
270	- - - - - - - - - - - - - - - - not determined -						
400	5	95	tr	0	95	tr	5
-400	tr	100	tr	0	100	tr	0

tr: trace (less than ~5%)

Cp: chalcopyrite
Cb: cubanite
Pn: pentlandite
Po: pyrrhotite
Ilm: ilmenite
Mag: magnetite

particles consist almost entirely of ilmenite or magnetite/gangue particles. Such an observation would indicate that coarse Cp-Cb/gangue particles were difficult to float, whereas fine locked particles with sulfides were completely floated. In fact, Po-Pn/gangue particles were seen to consist of relatively coarse pyrrhotite-pentlandite assemblages locked with silicate minerals. By contrast, a substantial portion of chalcopyrite occurred as fine inclusions in the silicates, mostly feldspar and pyroxene.

The 200- to 270-mesh size fractions of the C1 4 Concs were notably high in locked particles. This agrees with the observation mentioned in the preceding paragraph that much of the sulfide-bearing locked particles had been floated and that much of the locked particles were Cp-Cb/gangue. Free silicates and ilmenite/magnetite particles in the coarsest fraction must have been recovered accidentally by occlusion. The weight percent in that size fraction indicates that the number of these gangue particles was relatively small.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were analyzed in a similar manner after one week and one month of standing. The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 17 shows the amounts of residual flotation reagents in the liquors, Tables 18 and 19 the trace element analyses done by Barringer Research Ltd.

TABLE 17. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTIONS OF AX9002

Sampling Time	One-stage Grind Flotation (Test 15)			Two-stage Grind Flotation (Test 21)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	8.7	1.18	15.05	8.8	1.46	5.28
After 1 Day	8.5	0.88	18.77	8.5	0.74	5.34
After 1 Week	8.1	0.56	3.75	8.3	0.50	0.50
After 1 Month	8.3	0.24	0.00	8.1	0.46	0.00

TABLE 18. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9002 (TEST 15 - MINUS 200 MESH GRIND)

	Distilled Water (6-23-77)	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al	nd	2.35	1.15	0.82	0.28	0.18
B	nd	0.039	0.024	0.026	0.199	0.059
Ba	nd	nd	nd	nd	nd	nd
Be	nd	nd	nd	nd	nd	nd
Ca	nd	4.19	6.55	6.11	11.5	21.6
Cu	0.0983	0.0407	0.0064	0.0095	0.0065	0.0086
Fe	nd	2.15	0.887	0.271	0.036	0.079
K	nd	8.7	9.4	8.7	8.7	19.1
Mg	nd	1.74	1.95	1.25	2.38	4.98
Mn	nd	0.0207	0.0076	0.0044	nd	0.0074
Na	nd	39.4	25.3	28.2	26.3	28.5
P	nd	nd	nd	nd	nd	nd
Se	nd	nd	nd	nd	nd	nd
Te	nd	nd	nd	nd	nd	nd
Pb	nd	nd	nd	nd	nd	nd
Si	nd	6.37	4.47	4.49	4.49	6.00
Sr	nd	0.0147	0.0211	0.0170	0.0316	0.0557
Ti	0.0010	0.0434	0.0158	0.0056	0.0008	0.0027
V	nd	0.007	nd	0.004	0.001	0.006
Zn	nd	0.042	0.010	0.074	nd	0.318
Th	nd	nd	nd	nd	nd	nd
Ag	nd	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	nd
Cd	nd	nd	nd	nd	nd	nd
Co	nd	nd	nd	nd	nd	nd
Cr	nd	nd	nd	nd	nd	0.007
Mo	nd	nd	nd	nd	nd	0.05
Ni	nd	nd	nd	nd	0.03	nd
Zr	nd	nd	nd	nd	nd	nd

TABLE 19. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9002 (TEST 21 - MINUS 65 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		1.11	0.39	0.66	0.24	0.23
B		0.016	0.035	0.022	0.026	0.040
Ba		nd	nd	nd	nd	nd
Be		nd	nd	nd	nd	nd
Ca		4.45	27.3	6.12	10.4	14.3
Cu		0.0161	0.0135	0.0082	0.0075	0.009
Fe		0.329	0.029	0.113	0.113	0.063
K		3.8	9.0	7.6	10.1	13.3
Mg		0.599	2.34	1.27	1.78	2.55
Mn		nd	nd	nd	0.0024	0.0035
Na		15.9	22.6	20.2	18.1	24
P		nd	nd	nd	1.2	nd
Se		nd	nd	nd	nd	8
Te		nd	nd	nd	nd	nd
Pb		nd	0.1	nd	nd	nd
Si		3.13	2.99	3.51	6.00	4.76
Sr		0.0136	0.0457	0.0201	0.0557	0.0361
Ti		0.0094	0.0008	0.0012	0.0027	nd
V		nd	0.002	0.001	0.006	0.003
Zn		0.125	0.012	0.181	0.318	0.21
Th		nd	nd	nd	nd	nd
Ag		nd	nd	nd	nd	nd
As		nd	nd	nd	nd	nd
Cd		nd	nd	nd	nd	nd
Co		nd	nd	nd	nd	nd
Cr		0.008	0.006	0.014	0.008	0.011
Mo		0.67	nd	nd	0.16	0.26
Ni		0.03	0.05	0.06	nd	nd
Zr		nd	nd	nd	nd	nd

The pulp pH showed a tendency to decrease from a little above 9 during flotation to about 8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed appreciably in one week, and these reagents became virtually absent after one month. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors upon aging. Of particular interest is the fact that the concentration of copper remained less than 10 ppb throughout the period. In fact, these values were lower than those in the feed water prior to addition of the flotation reagents. The decrease upon the addition of these reagents may be interpreted to be due to the precipitation of insoluble copper xanthate. The concentrations of nickel ions in the pulp solutions remained essentially below the limit of detection by the analytical method used (90 ppb). Of note is the zinc ion concentration which eventually increased to a few tenths of one ppm in a month. Perhaps the zinc ions might have been released by the exchange reaction with copper and nickel ions.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet-screen results of Table 11. The size distributions of concentrates in the same range were determined by microscreening (Table 20). The data in the 'subsieve' range are of particular interest since the air-borne dusts are said to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200-mesh grind would have about 5 percent by weight of minus 5-μm particles and about 2 percent of minus 2-μm particles. At a 65-mesh grind, however, minus 5-μm particles would be about 3 percent and minus 2-μm particles

TABLE 20. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF AX9002

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 15 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	46.03	-
+20	78.40	23.92	80.38
+10	9.78	14.50	9.23
+5	5.40	15.55**	4.78
-5	6.42	-	4.78
	(b) Test 21 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	22.61	-
+20	92.30	37.94	93.54
+10	2.89	20.64	2.74
+5	1.13	18.81**	1.14
-5	3.68	-	2.58

* Cl 4 Conc and Regr Cl 4 Conc, respectively
**Minus 10 µm

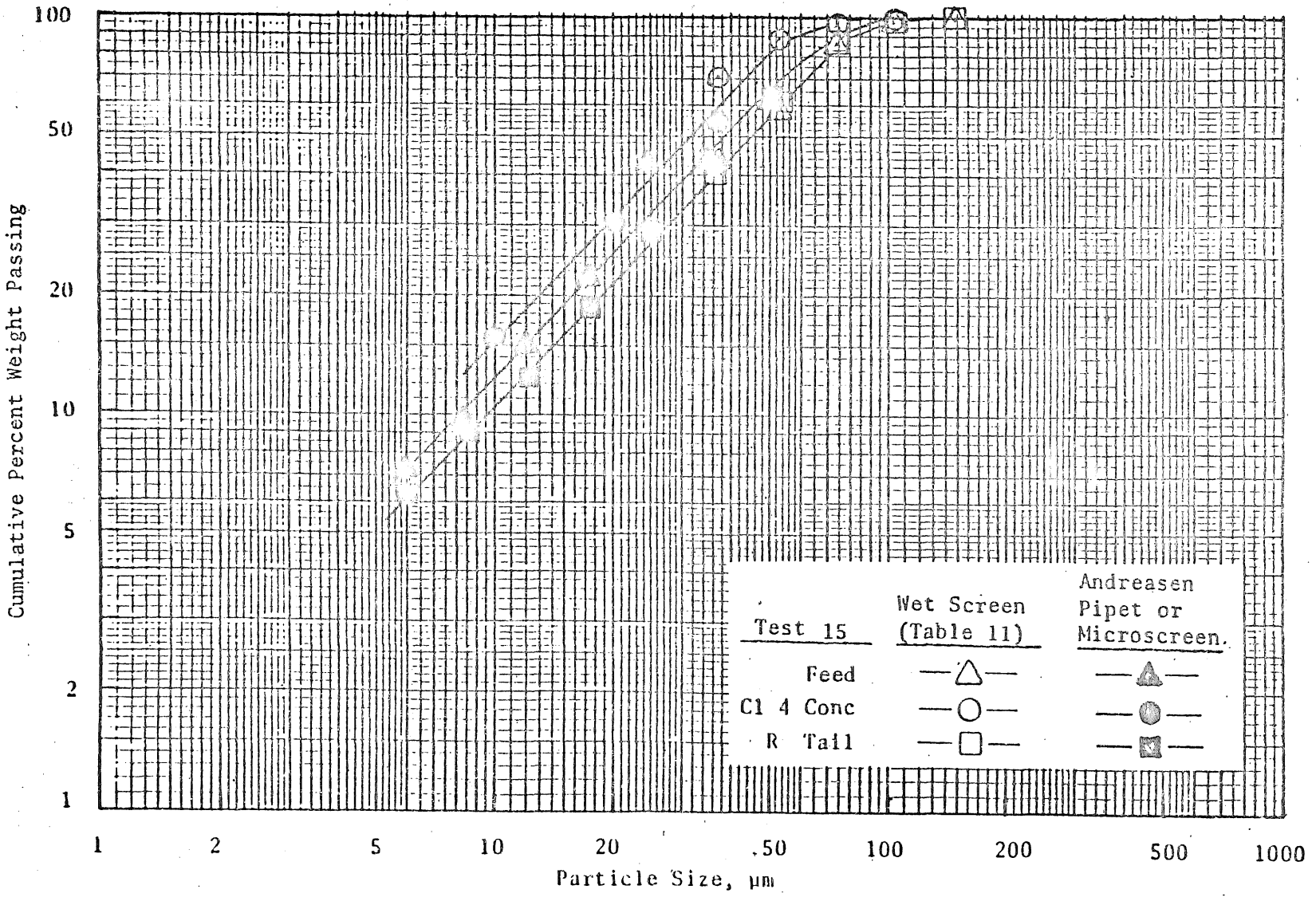


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF AX9002 SAMPLE (MINUS 200 MESH GRIND)

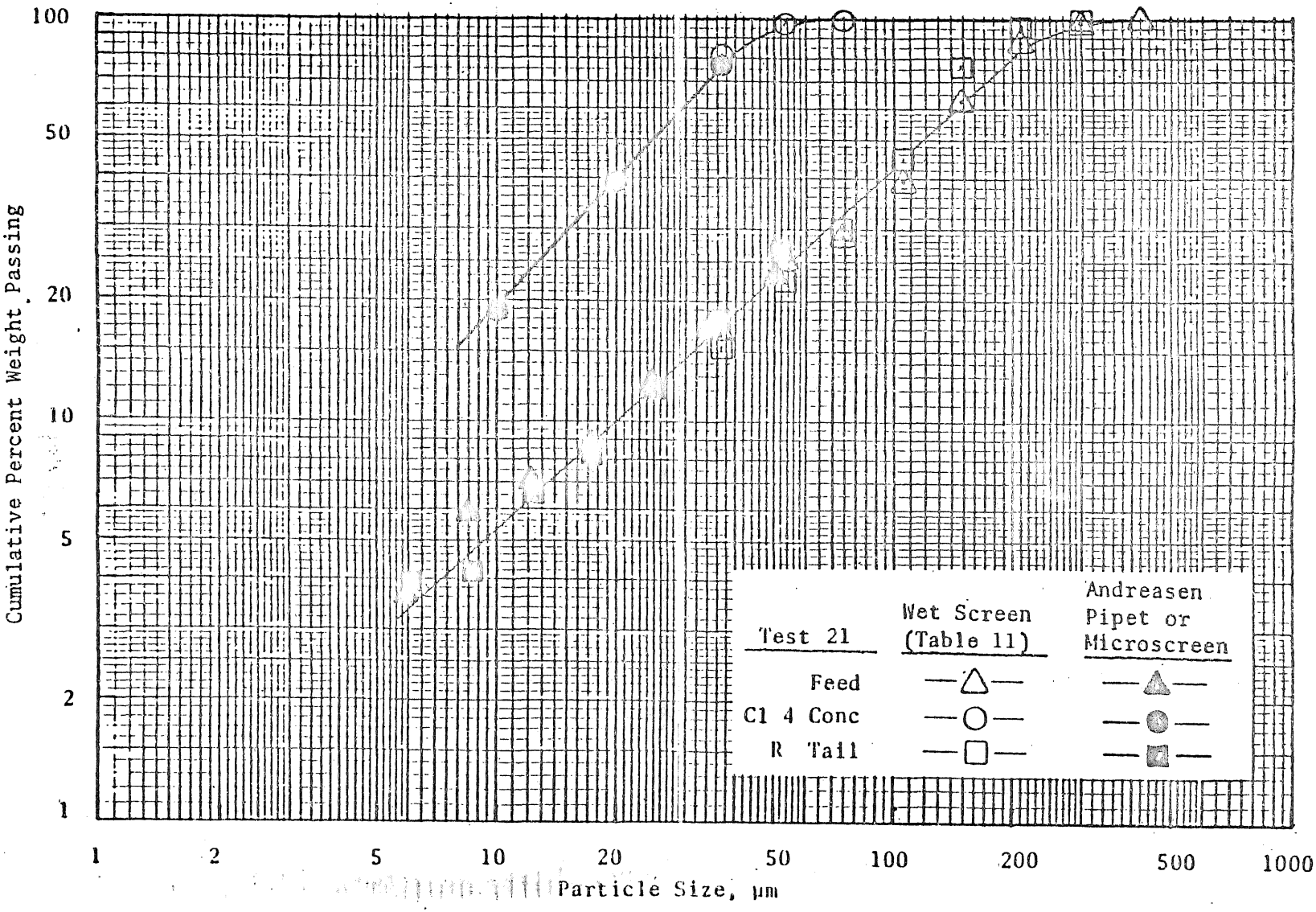


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF AX9002 (MINUS 65 MESH GRIND FOR FEED AND TAILING, MINUS 270 MESH GRIND FOR CONCENTRATE)

would be about 1.5 percent. The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

To investigate how various elements are distributed over different size fractions in the 'subsieve' range the feed and the rougher tailing samples were separated into +20, 20/10, 10/5 and -5 μm fractions by the sedimentation sizing method. The results are presented in Table 20. These results are in good agreement with those obtained by the Andreasen pipette method plotted in Figures 3 and 4. The size distributions of the concentrates were determined by microscreening to 10 μm, as explained in detail in the chapter on Procedure Development.

The analyses of each size fraction of the feed, concentrate and rougher tailing, reported by Barringer Research Ltd. are given in Tables 21 and 22. Except for copper in the rougher tailings, heavy metals are seen to be, more or less, evenly distributed over all the sizes. The copper contents in the minus 5-μm fraction in the rougher tailings are an order of magnitude higher than the other fractions. This particular point was already mentioned earlier in connection with Table 12. It is interesting to note that a similar trend was also noted for zinc although only in Table 21(a). The nickel content in the minus 5-μm fraction in the rougher tailings is about twice as high as the other fractions. Such an observation is also in agreement with the data in Table 12. Also of note in Table 22 is the presence of small amounts of arsenic over most of the size fractions of the flotation concentrate.

TABLE 21(a). TRACE ELEMENT ANALYSIS RESULTS IN PERCENT ON SIZE FRACTIONS OF FLOTATION PRODUCTS OF AX9002 (TEST 15 - ONE-STAGE GRIND FLOTATION)

	Feed				Rougher Tailing			
	+20 μm	20/10 μm	10/5 μm	-5 μm	+20 μm	20/10 μm	10/5 μm	-5 μm
Al	8.57	9.68	9.6	9.52	8.67	9.8	6.28	9.5
B	0.164	0.0756	0.0413	0.98	0.0711	0.0847	nd	0.0839
Be	nd	nd	nd	nd	0.00009	nd	nd	nd
Ca	5.20	5.5	5.46	5.05	5.21	5.59	3.65	5.38
Cu	0.488	0.635	0.432	0.621	0.019	0.0278	0.0281	0.104
Fe	9.41	8.0	7.95	8.66	9.39	7.87	5.6	8.29
Mg	2.87	2.5	2.5	2.64	2.92	2.92	2.03	2.67
Mn	0.122	0.0943	0.0948	0.105	0.131	0.131	0.0695	0.106
P	0.083	0.084	0.095	0.087	0.041	0.129	0.075	0.119
Ba	0.0696	0.0887	0.049	0.0967	0.0666	0.0887	0.0159	0.113
Se	nd	nd	nd	nd	nd	nd	nd	nd
[illegible]	nd	nd	nd	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	nd	nd	nd
Si	0.853	0.836	0.491	1.22	0.812	1.08	0.0221	1.32
Sr	0.0244	0.0277	0.0268	0.0273	0.0256	0.0278	0.0183	0.0272
Zr	0.00779	0.00649	0.00561	0.00667	0.00843	0.00805	0.00465	0.00712
Ti	0.997	0.867	0.912	0.9	1.28	1.07	0.742	0.989
V	0.0167	0.0149	0.0144	0.0143	0.018	0.016	0.0105	0.0149
Zn	0.0211	0.0214	0.0192	0.0242	0.0161	0.0138	0.0092	0.1840
Th	0.00138	0.00141	0.00142	0.00142	0.00032	0.00143	0.00096	0.00121
K	0.47	0.57	0.55	0.753	0.455	0.55	0.355	0.8
Na	1.97	2.14	2.05	1.98	2.04	2.04	1.39	2.09
Cd	0.002	0.0021	0.0021	0.0021	nd	0.0022	0.0012	0.0015
Cr	0.0157	0.0453	0.0604	0.045	0.00568	0.0728	0.0673	0.0562
Co	0.012	0.0112	0.011	0.0109	0.0083	0.0075	0.0049	0.0078
Ag	0.00035	0.00042	0.00042	0.00056	0.00023	0.00067	0.00015	0.00029
Mo	nd	0.0003	0.0012	0.0005	nd	0.0015	0.002	0.0014
Ni	0.0981	0.111	0.109	0.0986	0.0272	0.0324	0.0282	0.0458
Pb	0.004	0.003	0.004	0.007	nd	0.002	0.003	0.003

TABLE 21(b). TRACE ELEMENT ANALYSIS RESULTS IN PERCENT ON SIZE FRACTIONS OF FLOTATION PRODUCTS OF AX9002 (TEST 15 - ONE-STAGE GRIND FLOTATION)

	Cl 4 Conc (Sedimentation Sizing)				Cl 4 Conc (Microscreening)			
	+20 µm	20/10 µm	10/5 µm	-5 µm	+37 µm	37/20 µm	20/10 µm	-10 µm
Al	1.94	1.16	1.03	1.52	2.36	1.08	0.658	0.559
B	0.0089	nd	0.0031	nd	0.0082	0.0015	0.0026	0.0146
Be	nd	nd	nd	nd	nd	nd	nd	nd
Ca	1.2	0.675	0.573	0.795	1.46	0.65	0.389	0.402
Cu	18.1	22.0	21.3	21.1	16.5	20.2	22.6	23.9
Fe	21.4	20.6	19.7	19.2	20.4	22.5	22.7	22.1
Mg	1.23	1.34	1.71	1.64	1.37	0.955	0.91	0.813
Mn	0.0288	0.0251	0.0275	0.0278	0.0345	0.021	0.0177	0.0154
P	nd	nd	nd	nd	nd	nd	nd	nd
Ba	0.0099	0.006	0.0102	0.0044	0.0096	0.0044	0.0044	0.0149
Se	nd	nd	nd	nd	nd	nd	nd	nd
Te	nd	nd	nd	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	nd	nd	nd
Si	0.105	0.0253	0.0593	0.0356	0.106	0.0211	0.0269	0.167
Sr	0.00586	0.00334	0.00289	0.00425	0.00652	0.003	0.00165	0.00171
Zr	0.0015	0.00145	0.00135	0.00138	0.00186	0.00165	0.00128	0.00125
Ti	0.0695	0.0846	0.101	0.171	0.0953	0.0586	0.0545	0.0722
V	0.00823	0.00793	0.00775	0.00787	0.00873	0.0078	0.00742	0.00684
Zn	0.203	0.259	0.276	0.308	0.184	0.24	0.285	0.477
Th	0.00123	0.00094	0.00092	0.00096	0.00121	0.00116	0.00102	0.00102
K	0.07	0.03	0.035	0.08	0.8	0.086	0.04	0.025
Na	0.43	0.26	0.25	0.37	0.49	0.26	0.19	0.24
Cd	0.0043	0.0038	0.0045	0.004	0.0038	0.0042	0.0054	0.0043
Cr	0.0105	0.0089	0.0095	0.0166	0.00634	0.00536	0.00736	0.0195
Co	0.0854	0.0887	0.0769	0.0387	0.105	0.127	0.0955	0.0535
Ag	0.00414	0.00579	0.00661	0.00816	0.00382	0.00483	0.0056	0.00756
Mo	nd	0.0031	0.0032	0.0049	nd	nd	0.0014	0.0022
Ni	1.73	1.69	1.35	0.604	2.68	3.12	2.31	1.01
Pb	0.018	0.02	0.021	0.026	0.015	0.023	0.029	0.055

TABLE 22. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT ON SIZE FRACTIONS OF FLOTATION PRODUCTS OF AX9002 (TEST 21 - TWO-STAGE GRIND FLOTATION)

	Feed				Concentrate				Rougher Tailing			
	+20 μm	20/10 μm	10/5 μm	-5 μm	+37 μm	37/20 μm	20/10 μm	-10 μm	+20 μm	20/10 μm	10/5 μm	-5 μm
Al	8.8			9.88	0.782	1.45	0.782	0.435	9.55	12.1	12.2	10.1
B	nd			nd	nd	nd	nd	nd	nd	nd	nd	nd
Be	0.00008			0.00008	nd	nd	nd	nd	0.00008	0.00009	0.0001	0.00008
Ca	5.33			5.29	0.454	0.892	0.454	0.297	5.56	6.66	7.15	5.63
Cu	0.738			0.882	24.8	20.8	23.6	26.3	0.0569	0.079	0.101	0.153
Fe	12.0			11.2	27.3	27.7	28.5	28.6	11.6	8.32	9.67	10.6
Mg	4.51			4.4	1.61	1.27	1.08	0.956	4.7	3.63	4.38	4.41
Mn	0.136			0.124	0.0268	0.0268	0.0208	0.0156	0.146	0.0969	0.108	0.123
P	0.025			nd	nd	nd	nd	nd	0.044	0.037	0.02	0.041
Ba	0.0661			0.116	0.0053	0.0069	0.0035	0.0053	0.175	0.227	0.157	0.238
Se												
Te												
As	nd			nd	0.007	nd	0.002	0.006	nd	nd	nd	nd
Si	0.839			1.3	0.263	0.379	0.799	0.314	2.43	3.14	2.05	3.17
Sr	0.0265			0.0283	0.00186	0.00436	0.00242	0.0012	0.0302	0.038	0.038	0.0327
Zr	0.00745			0.0077	0.00177	0.00208	0.003	0.00148	0.0111	0.0136	0.0111	0.0119
Ti	1.39			0.931	0.122	0.0636	0.0474	0.0426	1.56	1.03	1.09	1.04
V	0.0185			0.0159	0.00769	0.00545	0.00535	0.0049	0.0201	0.016	0.0171	0.0164
Zn	0.0126			0.0203	0.221	0.0475	0.065	0.157	0.0125	0.0106	0.0138	0.0148
Th	0.00059			0.0008	nd	nd	nd	nd	0.00054	0.00068	0.0004	0.00061
K	0.588			1.17	0.011	0.014	nd	nd	0.613	0.92	0.704	1.24
Na	2.0			2.03	0.21	0.35	0.29	0.16	2.42	2.96	2.78	2.31
Cd	nd			nd	nd	nd	nd	nd	nd	nd	nd	nd
Cr	0.00896			0.0477	0.0783	nd	nd	0.0343	0.007	0.0383	0.0739	0.0749
Co	0.0131			0.0119	0.0789	0.156	0.155	0.107	0.008	0.0051	0.0047	0.0063
Ag	0.00036			0.00071	0.00506	0.00137	0.00558	0.00746	0.00014	0.00011	nd	0.00025
Mo	nd			0.0035	0.019	nd	nd	0.0011	nd	nd	nd	0.0052
Ni	0.168			0.171	1.36	4.21	4.13	2.72	0.0358	0.0376	0.05	0.0672
Pb	nd			0.002	0.0265	0.0015	0.0085	0.0296	nd	0.003	nd	nd

3.7 FLOTATION TESTS ON AX9003 SAMPLE

Sample Description

An AMAX shaft composite sample, labeled AX9003, weighing approximately 258 kilograms, was received on July 15, 1977, from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. This composite sample was reported to consist of the following individual round samples.

Sample Amount	Round	Depth	Assay
250 lb	211	1338	0.71 Cu 0.16 Ni 1.34 S
250 lb	212	1343	0.67 Cu 0.16 Ni 1.26 S

The whole sample received was stage-crushed to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF AX9003 SAMPLE

Constituent	Percent
Copper (Cu)	0.64
Nickel (Ni)	0.15
Cobalt (Co)	0.021
Iron (Fe)	11.04
Sulfur (S)	1.21
Titanium dioxide (TiO_2)	1.54
Graphite carbon (C)	0.18

Grinding Characteristics

The grinding characteristics of the crude sample were investigated by determining the size distribution of a 1200-gram lot ground in a stainless steel laboratory rod mill at 50 percent solids. The size distributions of the minus 10-mesh feed and of a sample ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. The size distribution data of the ground samples are seen to follow straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.91. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In the figure the experimental points of the IP9002 sample are also included. It is noted that these two sets of points may be represented by a common straight line. The grinding characteristics of these two Duluth gabbro samples, therefore, are quite similar. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF AX9003 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50% SOLIDS)

Nominal Mesh-of Grind	Grind Time Minutes	Size Modulus k, μm	80% passing μm
-10 mesh	0	-	820
-48 mesh	15	275	215
-65 mesh	20	215	170
-100 mesh	30	165	130
-200 mesh	60	100	78

TABLE 2. SCREEN ANALYSIS OF AX9003 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 Mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	-	-	-	-	-	-	-	-	-	-
+14	7.3	100.0	-	-	-	-	-	-	-	-
+20	10.0	92.7	-	-	-	-	-	-	-	-
+28	24.6	82.7	-	-	-	-	-	-	-	-
+35	11.8	58.1	0.2	100.0	-	-	-	-	-	-
+48	9.0	46.3	4.3	99.8	0.6	100.0	-	-	-	-
+65	7.0	37.3	13.1	95.5	5.2	99.4	0.2	100.0	-	-
+100	6.7	30.3	21.0	82.4	21.5	94.2	3.9	99.8	0.3	100.0
+150	6.7	23.6	22.2	61.4	29.4	72.7	29.2	95.9	10.7	99.7
+200	3.5	16.9	10.4	39.2	10.9	43.3	18.9	66.7	12.0	89.0
+270	3.4	13.4	6.7	28.8	8.9	32.4	17.5	47.8	22.2	77.0
+325	1.4	10.0	4.7	22.1	1.4	23.5	2.5	30.3	8.3	54.8
+400	1.7	8.6	0.5	17.4	2.4	22.1	2.1	27.8	6.7	46.5
+500	1.2	6.9	2.8	16.9	2.9	19.7	3.9	25.7	7.5	39.8
-500	5.7	5.7	14.1	14.1	16.8	16.8	21.8	21.8	32.3	32.3

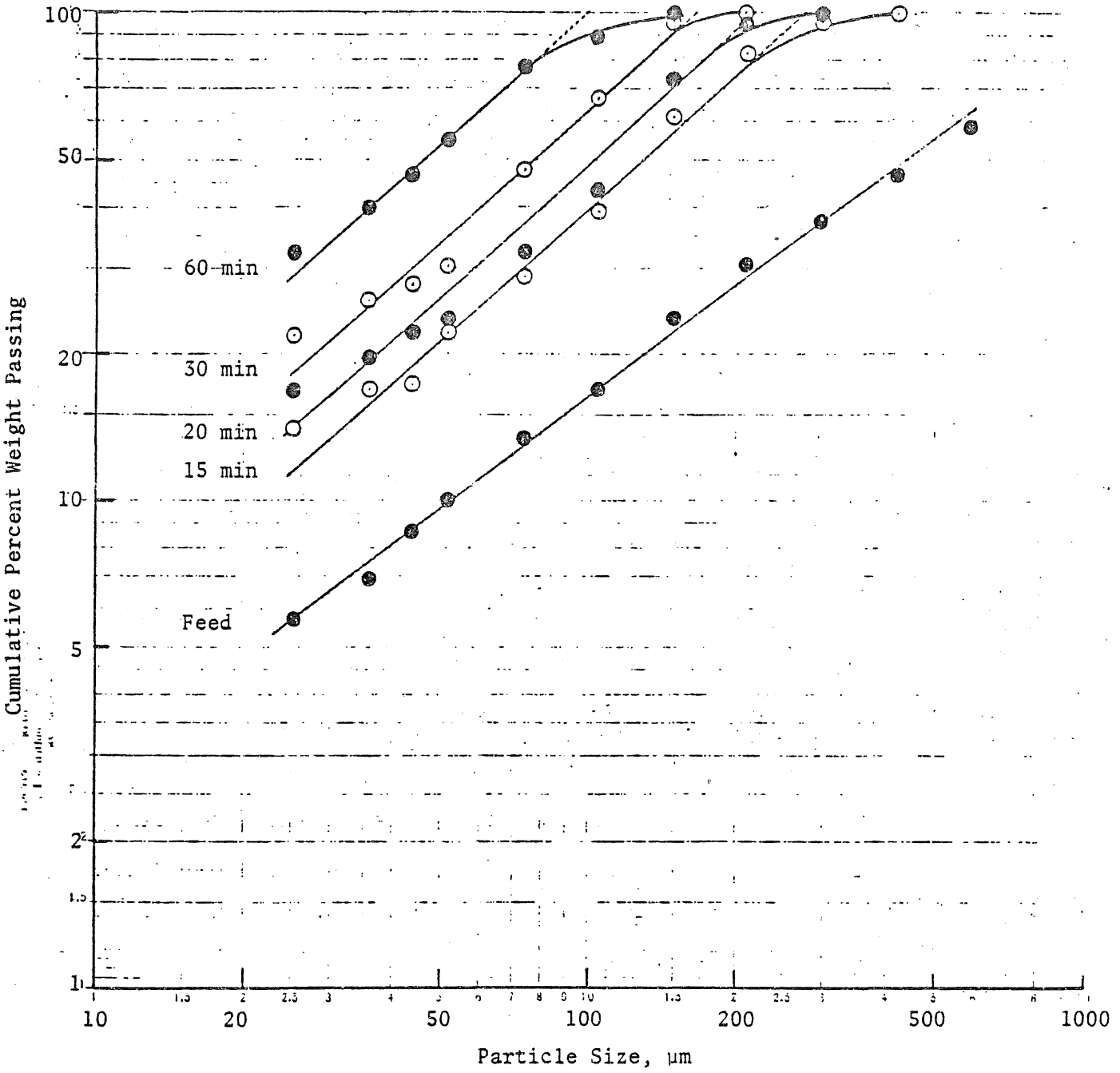


FIGURE 1. SIZE DISTRIBUTIONS OF AX9003 SAMPLE AS A FUNCTION OF GRINDING TIME

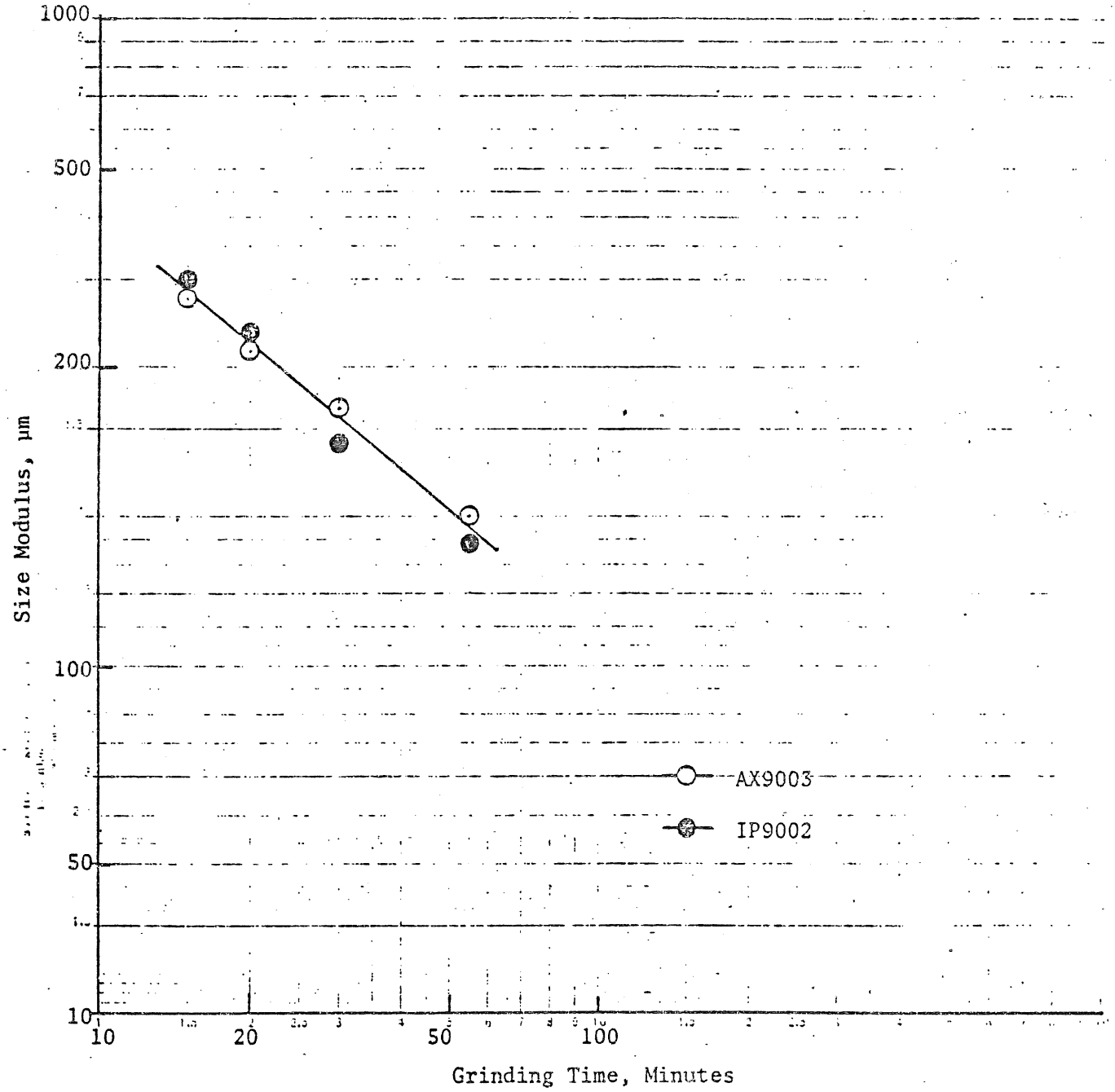


FIGURE 2. SIZE MODULI OF AX9003 AND IP9002 SAMPLES AS A FUNCTION OF GRINDING TIME

Preliminary Flotation Tests

The effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10 mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh, and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 10 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed also at 5 minutes. The results of these flotation tests are given in Table 4.

It is apparent in Table 4 that the loss of copper to the R Tails improved to about 4 percent as the mesh-of-grind became finer and the loss of nickel remained more or less constant at 20-25 percent in the range of minus 65 to 200-mesh grind samples. The losses of copper and nickel to R Tails tended to increase somewhat at 48 mesh. It is also noted that the concentrates after three cleaner stages analyzed in excess of 14 percent copper and approached 2.4 percent nickel. These observations are similar to the flotation behaviors of another AMAX shaft composite sample (AX9002).

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 94.96%, 73.00%, and 94.33%, respectively, at 200 mesh (one-stage grind flotation), and were 90.54%, 64.87%, and 87.86%,

TABLE 4. EFFECT OF MESH-OF-GRIND ON AX9003
Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Flotation Time: Rougher 10 min, Cleaner 5 min

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	4.75	9.86	1.61	79.53	45.58	4.75	9.86	1.61	79.53	45.58
		Cl 4 Tail	1.74	1.21	1.00	3.58	10.37	6.49	7.54	1.44	83.11	55.95
		Cl 3 Tail	1.96	0.84	0.55	2.80	6.44	8.45	5.99	1.24	85.91	62.39
		Cl 2 Tail	1.76	0.69	0.32	2.05	3.34	10.21	5.07	1.08	87.96	65.73
		Cl 1 Tail	5.54	0.185	0.11	1.75	3.64	15.75	3.36	0.74	89.71	69.37
		R Tail	84.25	0.072	0.061	10.29	30.63	100.00	0.59	0.17	100.00	100.00
2	65	Cl 4 Conc	3.45	16.36	2.44	80.40	44.57	3.45	16.37	2.44	80.40	44.57
		Cl 4 Tail	0.63	1.87	2.01	1.68	6.72	4.08	14.12	2.38	82.08	51.29
		Cl 3 Tail	1.40	1.22	1.40	2.44	10.38	5.48	10.82	2.13	84.52	61.67
		Cl 2 Tail	3.43	0.76	0.56	3.72	10.16	8.91	6.95	1.52	88.24	71.83
		Cl 1 Tail	7.69	0.25	0.15	2.74	6.09	16.60	3.85	0.89	90.98	77.92
		R Tail	83.40	0.076	0.05	9.02	22.08	100.00	0.70	0.19	100.00	100.00
3	100	Cl 4 Conc	3.74	14.15	1.98	82.75	38.98	3.74	14.15	1.98	82.75	38.98
		Cl 4 Tail	0.93	1.53	2.00	2.22	9.78	4.67	11.64	1.99	84.97	48.76
		Cl 3 Tail	1.59	0.93	0.94	2.36	7.89	6.26	8.92	1.72	87.33	56.65
		Cl 2 Tail	3.35	0.55	0.38	2.88	6.68	9.61	6.00	1.25	90.21	63.33
		Cl 1 Tail	7.56	0.16	0.10	1.89	4.00	17.17	3.43	0.75	92.10	67.33
		R Tail	82.83	0.061	0.075	7.90	32.67	100.00	0.64	0.19	100.00	100.00
4	200	Cl 4 Conc	3.60	16.01	2.32	89.60	47.84	3.60	16.01	2.32	89.60	47.84
		Cl 4 Tail	0.57	1.27	1.51	1.12	4.93	4.17	14.00	2.21	90.72	52.77
		Cl 3 Tail	1.38	0.59	0.74	1.26	5.85	5.55	10.66	1.84	91.98	58.62
		Cl 2 Tail	5.39	0.29	0.36	2.43	11.12	10.94	5.55	1.11	94.41	69.74
		Cl 1 Tail	17.14	0.072	0.09	1.91	8.83	28.08	2.21	0.49	96.32	78.57
		R Tail	71.92	0.033	0.052	3.68	21.43	100.00	0.64	0.18	100.00	100.00
5	Rghr 65 Regr 270	Regr Cl 4 C	2.74	18.78	2.68	84.32	46.33	2.74	18.78	2.68	84.32	46.33
		Regr Cl 4 T	0.15	2.75	3.71	0.67	3.54	2.89	17.95	2.73	84.99	49.87
		Regr Cl 3 T	0.25	1.31	1.75	0.54	2.78	3.14	16.62	2.66	85.53	52.65
		Regr Cl 2 T	0.89	0.79	0.79	1.15	4.42	4.03	13.13	2.24	86.68	57.07
		Regr Cl 1 T	4.90	0.30	0.37	2.41	11.43	8.93	6.09	1.22	89.09	68.50
		Cl Tail	8.57	0.20	0.10	2.80	5.43	17.50	3.21	0.67	91.89	73.93
		R Tail	82.50	0.06	0.05	8.11	26.07	100.00	0.61	0.16	100.00	100.00

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON AX9003

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 6 Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 10 min Pulp Temperature: 23.5°C Rougher pH: 9.4							
Cl 4 Conc	3.93	14.00	2.54	0.12	28.18	23.11	2.80
Cl 4 Tail	0.49	1.02	1.41	0.075	16.84	6.03	-
Cl 3 Tail	1.02	0.56	0.67	0.037	15.43	4.05	-
Cl 2 Tail	3.27	0.23	0.32	0.024	13.25	2.67	-
Cl 1 Tail	12.20	0.114	0.123	0.018	11.81	1.35	-
R Tail	79.09	0.039	0.065	0.013	10.12	0.093	-
Flotation Feed	100.00	0.60	0.19	0.020	11.50	1.30	0.18
Test No. 7 Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 29°C Rougher pH: 9.3							
Regr Cl 4 Conc	2.80	18.61	2.58	0.14	30.60	27.87	3.61
Regr Cl 4 Tail	0.17	2.60	3.56	0.198	21.91	11.66	-
Regr Cl 3 Tail	0.26	1.19	2.27	0.113	18.86	8.28	-
Regr Cl 2 Tail	0.83	0.65	0.73	0.048	15.35	5.49	-
Regr Cl 1 Tail	4.83	0.24	0.17	0.019	11.85	2.57	-
Cl Tail	7.43	0.21	0.13	0.016	11.81	1.33	-
R Tail	83.68	0.07	0.07	0.013	9.50	0.18	-
Flotation Feed	100.00	0.60	0.132	0.018	9.52	1.22	

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON AX9003

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 6 One-stage Grind Flotation																	
Cleaner 4	3.93	14.00	2.54	0.120	28.18	23.11	89.72	52.41	25.00	9.89	69.58	96.07	0.066	0.094	0.015	10.52	0.41
Cleaner 3	4.42	12.56	2.41	0.115	26.92	21.22	90.54	56.03	27.13	10.60	71.88	95.58	0.061	0.088	0.014	10.49	0.38
Cleaner 2	5.44	10.31	2.07	0.101	24.82	18.00	91.47	59.60	29.26	12.03	75.02	94.56	0.055	0.081	0.014	10.44	0.35
Cleaner 1	8.71	6.53	1.42	0.072	20.44	12.24	92.69	65.12	33.52	15.86	81.69	91.29	0.049	0.073	0.014	10.34	0.26
Rougher	20.91	2.79	0.67	0.041	15.40	5.89	94.96	73.00	45.22	28.69	94.33	79.09	0.039	0.065	0.013	10.12	0.093
Test No. 7 Two-stage Grind Flotation																	
Regr Cleaner 4	2.80	18.61	2.58	0.14	30.60	27.87	84.07	43.28	21.79	8.21	62.89	97.20	0.102	0.097	0.014	9.89	0.47
Regr Cleaner 3	2.97	17.69	2.64	0.141	30.30	26.94	84.78	46.94	23.47	8.59	64.49	97.03	0.097	0.091	0.014	9.87	0.45
Regr Cleaner 2	3.23	16.37	2.61	0.139	29.41	25.44	85.28	50.47	25.15	9.07	66.22	96.77	0.094	0.085	0.014	9.85	0.43
Regr Cleaner 1	4.06	13.15	2.22	0.121	26.60	21.36	86.15	54.13	27.38	10.31	69.90	95.94	0.089	0.080	0.014	9.80	0.39
Cleaner	8.89	6.14	1.11	0.065	18.56	11.15	88.02	59.05	32.41	15.75	79.90	91.11	0.081	0.075	0.013	9.69	0.27
Rougher	16.32	3.44	0.66	0.043	15.50	6.69	90.54	64.87	39.11	24.15	87.86	83.68	0.070	0.07	0.013	9.50	0.18

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF AX9003

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+150	2.71	-	2.28
+200	3.40	3.99	12.14
+270	29.41	11.30	32.30
+400	12.92	19.93	6.41
-400	51.56	64.78	46.87
(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)			
+48	0.64	-	0.64
+65	5.79	-	6.41
+100	22.37	-	21.11
+150	23.15	-	28.96
+200	16.15	-	14.40
+270	6.86	3.77	6.31
+400	3.53	8.79	4.05
-400	21.51	87.44	18.12

*Cl 4 Conc and Regr Cl 4 Conc, respectively

respectively, at 65 mesh (two-stage grind flotation). The flotation concentrate could be upgraded to 12.56 percent copper and 2.41 percent nickel in the one-stage grind flotation after three cleanings, whereas in the two-stage grind flotation the concentrate was upgraded to 13.15 percent copper and 2.22 percent nickel after one cleaning following regrinding. The sum of the copper, nickel, cobalt, iron, and sulfur contents may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The third cleaner concentrate (Cl 3 Conc) in the one-stage grind flotation would then have 36.8 percent gangue and the reground first cleaner concentrate (Regr Cl 1 Conc) in the two-stage grind flotation would have 36.5 percent gangue.

A Davis magnetic tube test was performed on a Cl 4 Conc sample to explore the feasibility of a copper-nickel separation, but the magnetic concentrate amounted to only 1.64 percent by weight. Hence, chemical analyses on the magnetic separation products were not made. Evidently, the pyrrhotite in the present sample is the nonmagnetic variety.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, and R Tail samples in the one-stage grind flotation test and the Feed, Regr Cl 4 Conc, Cl Tail, and R Tail samples in the two-stage grind flotation test were analyzed by Barringer Research Ltd. The results are given in Tables 7 and 8. In these tables it is seen that the concentration of such trace elements as zinc and silver notably increased. The amount of lead in the cleaner concentrates increased to some extent. These increases are apparently due to the close association of these elements with sulfide minerals. The copper, nickel, iron and cobalt analyses by Barringer and by the MRRC are seen to be in reasonably good agreement. The

TABLE 7. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9003 (TEST 6 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.62		2.5				8.94	
B	0.0241		0.0123				0.0217	
Be	0.00009		nd				0.00009	
Ca	4.84		1.41				4.97	
Cu	0.59	0.60	14.0	14.00			0.0195	0.039
Fe	10.0	11.50	21.6	28.18			9.16	10.12
Mg	4.48		2.09				4.56	
Mn	0.113		0.0377				0.117	
P	0.071		0.354				0.059	
Ba	0.0326		0.0072				0.0323	
Se	nd		nd				nd	
Te	nd		nd				nd	
As	nd		nd				nd	
Si	0.274		0.0386				0.231	
Sr	0.0227		0.00651				0.0239	
Zr	0.00704		0.00239				0.00837	
Ti	1.02		0.12				1.11	
V	0.0185		0.00632				0.0192	
Zn	0.0199		0.1610				0.0116	
Th	nd		nd				nd	
K	0.376		0.112				0.399	
Na	1.75		0.41				1.83	
Cd	nd		nd				nd	
Cr	0.0426		0.017				0.0322	
Co	0.0114	0.020	0.109	0.12			0.0062	0.013
Ag	0.00025		0.00329				0.00009	
Mo	nd		0.0064				nd	
Ni	0.13	0.19	2.25	2.54			0.0285	0.065
Pb	nd		0.009				nd	

*Conventional AA analyses

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9003 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.76		1.27		8.57		8.97	
B	0.0196		nd		0.0299		0.0197	
Be	0.00009		nd		0.00009		0.00009	
Ca	4.77		0.716		4.61		5.02	
Cu	0.595	0.60	18.0	18.61	0.188	0.21	0.036	0.07
Fe	9.7	9.52	32.7	30.60	10.3	11.81	9.32	9.50
Mg	4.39		1.31		4.62		4.57	
Mn	0.111		0.0222		0.113		0.118	
P	0.081		0.455		0.075		0.06	
Ba	0.0295		0.0058		0.0375		0.0302	
Se	nd		nd		nd		nd	
Te	nd		nd		nd		nd	
As	nd		nd		nd		nd	
Si	0.203		0.0261		0.311		0.214	
Sr	0.0232		0.00324		0.0224		0.0242	
Zr	0.00711		0.00197		0.00737		0.00771	
Ti	0.94		0.0642		0.843		1.18	
V	0.018		0.00368		0.019		0.0194	
Zn	0.019		0.019		0.0147		0.0126	
Th	nd		nd		nd		nd	
K	0.376		0.066		0.423		0.365	
Na	1.79		0.19		1.68		1.84	
Cd	nd		nd		nd		nd	
Cr	0.0177		0.00193		0.0435		0.016	
Co	0.0109	0.018	0.117	0.14	0.0098	0.016	0.0065	0.013
Ag	0.0002		0.00371		0.00025		0.0001	
Mo	nd		0.0062		nd		nd	
Ni	0.115	0.132	2.5	2.58	0.0954	0.13	0.027	0.07
Pb	nd		0.004		nd		nd	

*Conventional AA analyses

silicon analyses in Tables 7 and 8 appear to be unreasonably low since the feed and tailing samples were essentially silicates.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tialing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were analyzed in a similar manner after one week and one month of standing. The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 9 shows the amounts of residual flotation reagents in the liquors. Tables 10 and 11 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease from near 9 during flotation to about 8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed appreciably in one week, and these reagents became virtually absent after one month. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors upon aging. Of particular interest is the fact that the concentration of copper remained near 10 ppb throughout the period. In fact, these values were lower than those in the distilled water used at the time. The decrease in the presence of the ore sample may be interpreted to be due to adsorption and that upon the addition of flotation reagents to the precipitation of insoluble copper xanthate. The concentrations of nickel ions in the pulp solutions remained below the limit of detection by the analytical method used (90 ppb). Of note is the zinc-ion concentration which eventually increased to a few tenths of

TABLE 9. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTION OF AX9003

Sampling Time	One-stage Grind Flotation (Test 6)			Two-stage Grind Flotation (Test 7)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	9.0	2.10	8.40	8.9	2.00	10.73
After 1 Day	8.9	0.865	8.06	8.7	0.856	6.82
After 1 Week	8.7	0.659	2.79	8.2	0.763	2.28
After 1 Month	8.1	0.254	0.00	8.1	0.266	0.00

TABLE 10. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9003 (TEST 6 - MINUS 200 MESH GRIND)

	Distilled Water (8-30-77)	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al	nd	1.03	1.22	0.75	0.57	0.21
B	nd	0.023	0.007	0.023	0.025	10.0
Ba	nd	nd	nd	nd	nd	0.07
Be	nd	nd	nd	nd	nd	nd
Ca	nd	3.04	4.78	5.22	6.74	14.5
Cu	0.078	0.01	0.015	0.022	0.008	0.017
Fe	nd	0.41	1.02	0.434	0.35	0.1
K	nd	9.2	11.0	10.4	11.0	18.4
Mg	nd	0.644	1.63	1.24	1.39	2.69
Mn	nd	0.0035	0.007	0.0035	0.0035	nd
Na	nd	41	34	33	33	30
P	nd	nd	nd	nd	nd	nd
Se	nd	nd	nd	nd	nd	nd
Te	nd	nd	nd	nd	nd	nd
Pb	nd	nd	nd	nd	nd	nd
Si	nd	3.79	4.03	3.65	4.18	5.18
Sr	nd	0.0116	0.0173	0.0173	0.0202	0.0402
Ti	nd	0.005	0.02	0.008	0.006	0.002
V	nd	0.005	0.006	0.004	0.005	0.004
Zn	nd	nd	0.05	0.08	0.24	0.05
Th	nd	nd	nd	nd	nd	0.007
Ag	0.004	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	nd
Cd	nd	nd	nd	nd	0.12	nd
Co	nd	nd	nd	nd	nd	nd
Cr	nd	0.021	0.015	0.008	0.008	nd
Mo	0.12	0.32	0.22	0.31	0.35	0.08
Ni	nd	nd	nd	nd	nd	nd
Zr	nd	nd	nd	nd	nd	0.001

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9003 (TEST 7 - MINUS 65 MESH GRIND)

	Distilled Water (9-1-77)	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al	0.05	0.78	0.74	0.67	0.39	0.11
B	nd	0.023	0.017	0.013	0.031	10.0
Ba	nd	nd	nd	nd	nd	0.04
Be	nd	nd	nd	nd	nd	nd
Ca	nd	4.13	5.87	5.65	7.16	14.5
Cu	0.131	0.029	0.10	0.010	nd	0.017
Fe	0.016	0.038	0.302	0.196	0.188	0.029
K	nd	6.4	9.5	10.0	14	23.5
Mg	0.050	1.29	1.53	1.24	1.46	4.12
Mn	nd	0.0035	0.0035	nd	nd	nd
Na	nd	31	26	27	30	33
P	nd	nd	nd	nd	nd	nd
Se	nd	nd	nd	nd	nd	nd
Te	nd	nd	nd	nd	nd	nd
Pb	nd	nd	nd	nd	nd	nd
Si	0.009	2.70	2.85	3.06	4.28	5.59
Sr	nd	0.013	0.0202	0.0188	0.0229	0.055
Ti	nd	nd	0.009	0.004	0.002	0.001
V	nd	0.004	0.003	0.003	nd	0.003
Zn	nd	0.33	nd	0.05	0.16	nd
Th	nd	nd	nd	nd	nd	nd
Ag	0.009	nd	nd	nd	nd	nd
As	nd	nd	nd	nd	nd	nd
Cd	0.12	0.12	nd	nd	nd	nd
Co	nd	nd	nd	nd	nd	nd
Cr	nd	nd	nd	nd	nd	0.008
Mo	0.12	0.20	0.31	0.29	nd	0.08
Ni	nd	nd	nd	nd	nd	nd
Zr	nd	nd	nd	nd	nd	nd

one ppm in a month. Perhaps the zinc ions might have been released by the exchange reaction with copper and nickel ions.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of Table 6. The size distributions of concentrates in the same range were determined by microscreening (Table 12). The data in the 'subsieve' range are of particular interest since the air-borne dusts are said to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200 mesh grind would have about 6.5 percent by weight of minus 5-μm particles. At a 65-mesh grind, however, minus 5-μm particles would be about 2.5 percent. The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

TABLE 12. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF AX9003

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	39.53	-
+20	74.44	27.74	78.11
+10	11.02	15.26	10.62
+5	6.46	17.47**	5.11
-5	8.08	-	6.16
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	16.62	-
+20	87.75	37.59	91.46
+10	4.74	21.42	3.86
+5	3.23	24.37**	1.91
-5	4.28	-	2.77

* Cl 4 Conc and Regr Cl 4 Conc, respectively
**Minus 10 µm

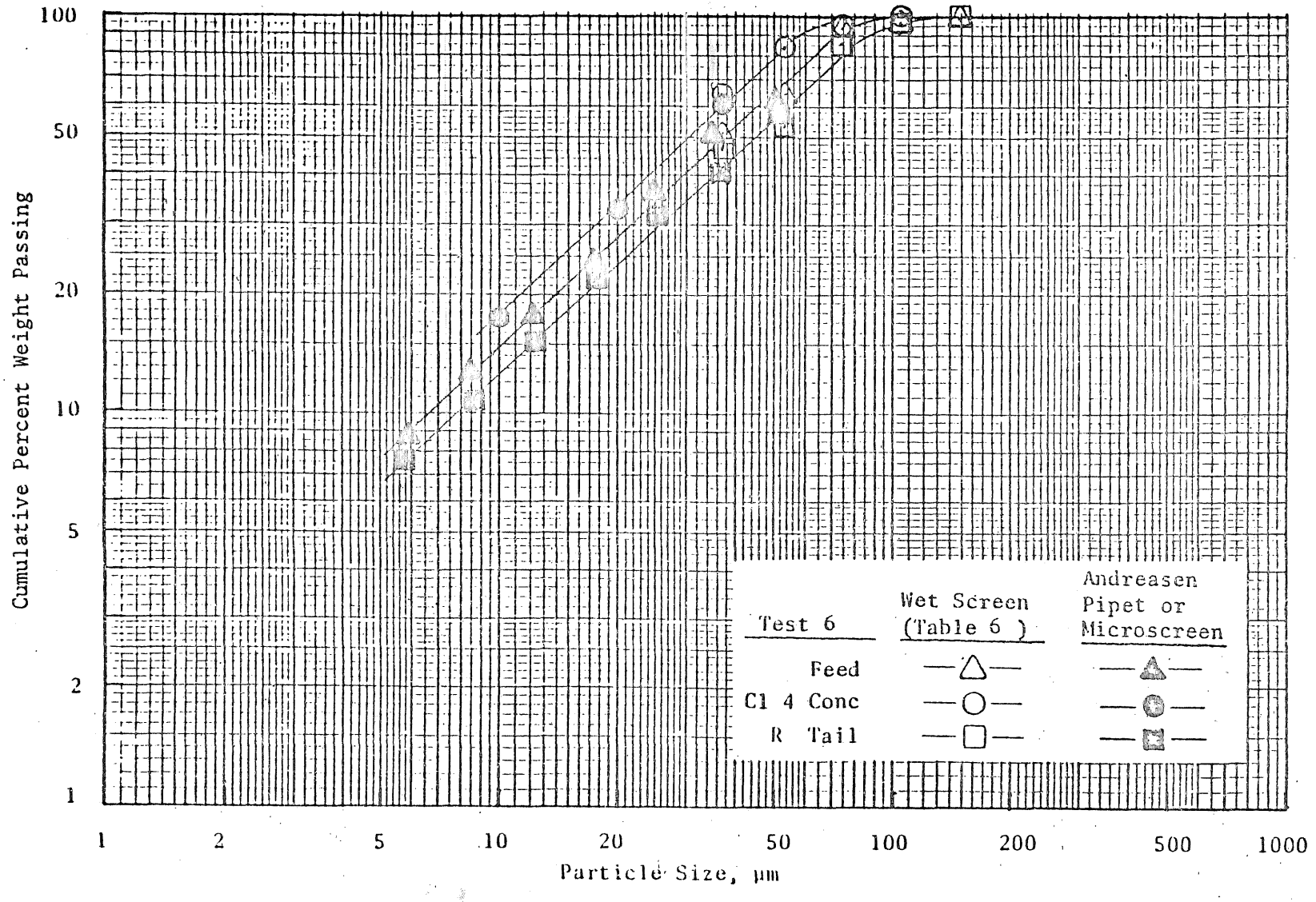


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF AX9003 (MINUS 200 MESH GRIND)

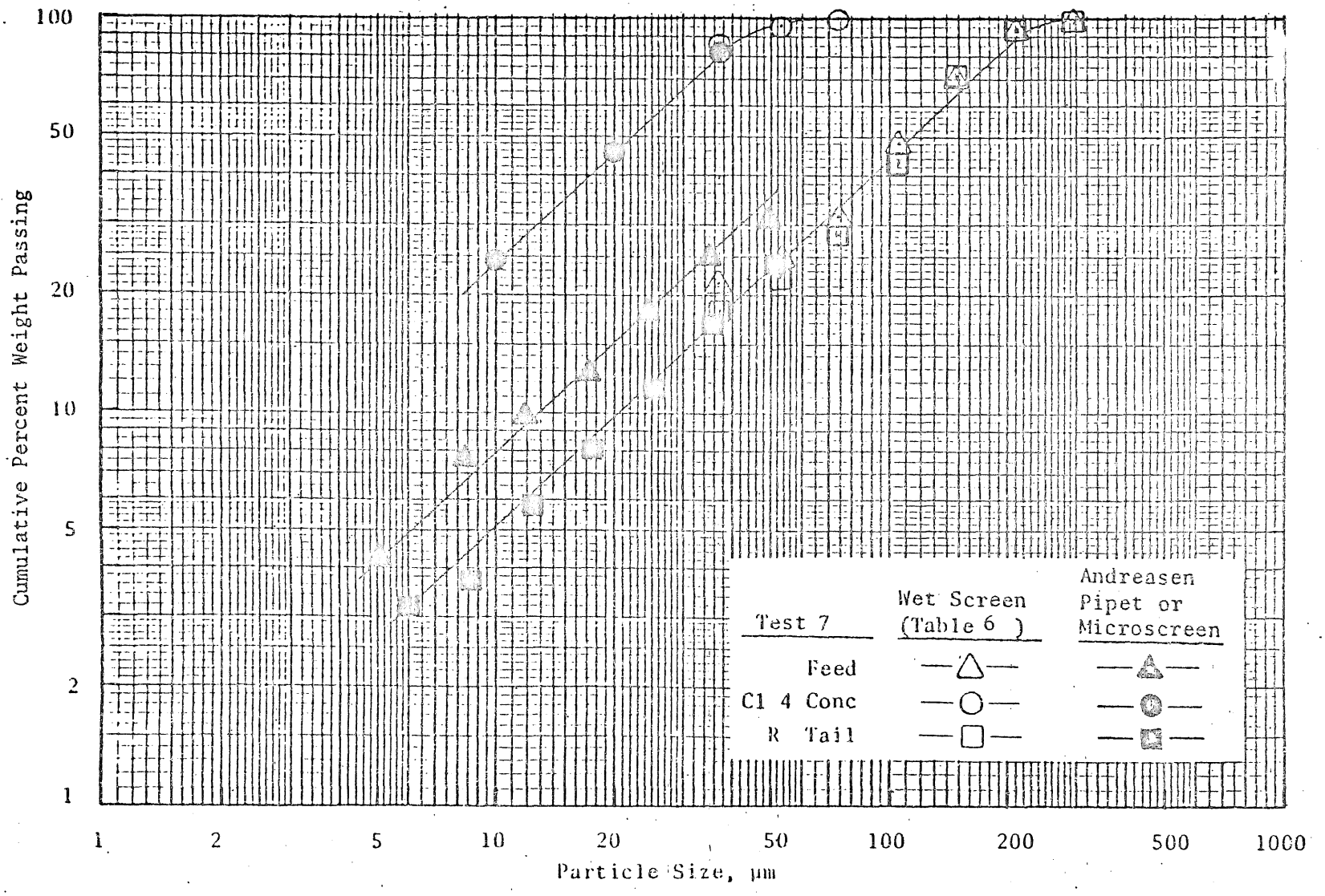


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF AX9003
(MINUS 65 MESH FOR FEED AND TAILING, MINUS 270 MESH FOR CONCENTRATE)

3.8 FLOTATION TESTS ON AX9004 SAMPLE

Sample Description

An AMAX mineralized rock sample, labeled AX9004, weighing approximately 275 kilograms, was received on September 12, 1977, from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. This semi-massive, mineralized rock sample was reported to have been collected from Round No. 65 in the AMAX "A" drift. This round pulled five feet of rock (136.5 to 141.5 feet from the shaft). The depths of this round are: back of drift - 1,674 feet and bottom - 1,683 feet.

The whole sample received was stage-crushed to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF AX9004 SAMPLE

Constituent	Percent
Copper (Cu)	1.30*
Nickel (Ni)	0.56**
Cobalt (Co)	0.038
Iron (Fe)	19.48
Sulfur (S)	8.42
Titanium dioxide (TiO_2)	1.17
Graphite carbon (C)	0.22

* Average of 13 analyses ranging 1.00-1.53% Cu
**Average of 13 analyses ranging 0.34-0.64% Ni

Grinding Characteristics

The grinding characteristics of the AX9004 sample were investigated by grinding 1200-gram batches of minus 10-mesh feed in a stainless steel laboratory rod mill at 50 percent solids for various periods of time. The size distributions of the minus 10-mesh feed and of a sample ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. The size distribution data of the ground batches are seen to be represented by straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.70. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF AX9004 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50 PERCENT SOLIDS)

Nominal Mesh-of-Grind	Grind Time Minutes	Size Modulus k, µm	80% passing µm
-10 mesh	0	-	1000
-48 mesh	15	285	208
-65 mesh	20	200	146
-100 mesh	30	135	97
-200 mesh	60	82	59

Preliminary Flotation Tests

The effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample toa nominal minus 48 mesh, minus 65 mesh, minus 100 mesh, and minus 200 mesh and by performing a standardized

TABLE 2. SCREEN ANALYSIS OF AX9004 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 Mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	0.3	100.0	-	-	-	-	-	-	-	-
+14	8.9	99.7	-	-	-	-	-	-	-	-
+20	10.2	90.8	-	-	-	-	-	-	-	-
+28	26.4	80.6	-	-	-	-	-	-	-	-
+35	11.1	54.2	-	-	-	-	-	-	-	-
+48	8.0	43.1	0.8	100.0	-	-	-	-	-	-
+65	7.7	35.1	15.2	99.2	1.9	100.0	-	-	-	-
+100	5.8	27.4	19.0	84.0	16.5	98.1	0.5	100.0	-	-
+150	4.5	21.6	14.0	65.0	19.6	81.6	16.8	99.5	0.2	100.0
+200	5.0	17.1	12.5	51.0	12.0	62.0	4.7	82.7	7.5	99.8
+270	2.6	12.1	8.2	38.5	9.5	50.0	28.5	78.0	16.4	92.3
+325	1.0	9.5	3.3	30.3	3.7	40.5	5.5	49.5	13.7	75.9
+400	0.8	8.5	5.0	27.0	6.8	36.8	2.2	44.0	6.2	62.2
+500	1.2	7.7	1.5	22.0	6.0	30.0	8.8	41.8	7.0	56.0
-500	6.5	6.5	20.5	20.5	24.0	24.0	33.0	33.0	49.0	49.0

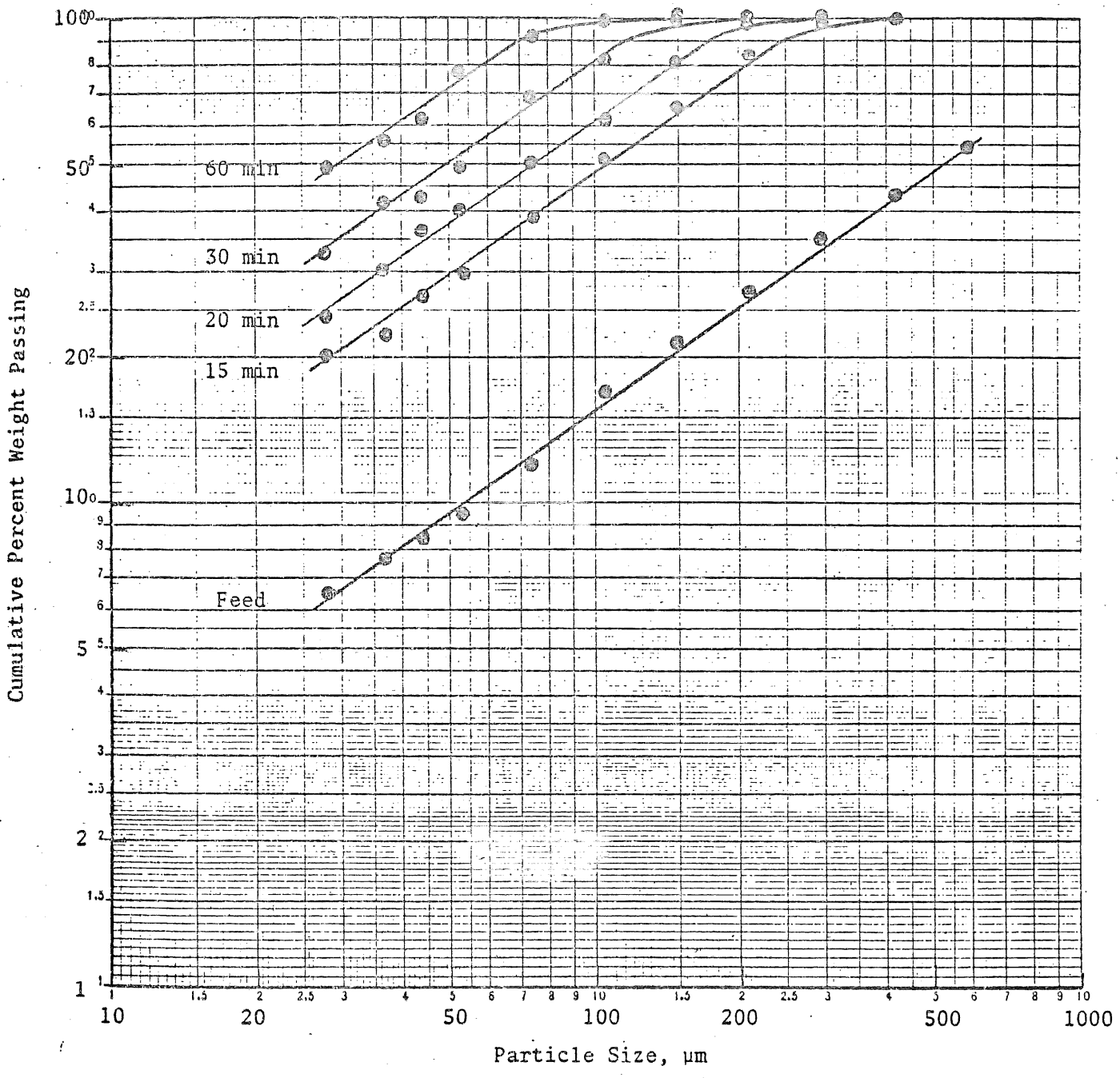


FIGURE 1. SIZE DISTRIBUTIONS OF AX9004 SAMPLE AS A FUNCTION OF GRINDING TIME

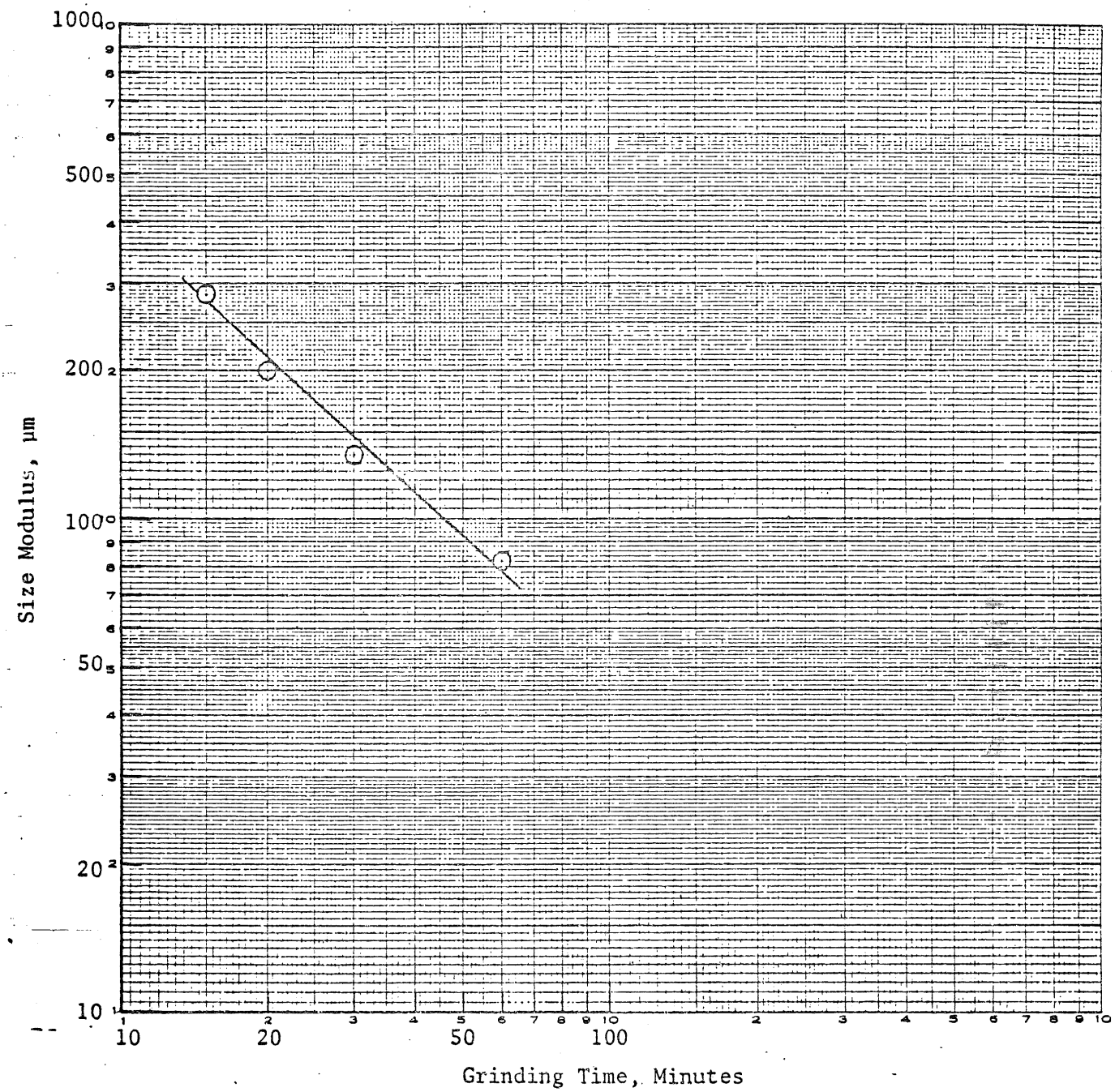


FIGURE 2. SIZE MODULI OF AX9004 SAMPLE AS A FUNCTION OF GRINDING TIME

flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed at 5 minutes. The results of these flotation tests are given in Table 4.

Judging from the copper and nickel analysis data of rougher tailings (R Tail), which remained approximately constant at 0.04 to 0.05 percent and 0.03 percent, respectively, the losses of copper and nickel to R Tails did not depend on the mesh-of-grind in the stated size range. It is also noted that the concentrates after four cleaner stages analyzed only 6 to 8.4 percent copper. Even in the two-stage grind flotation test the concentrate grade did not improve too much beyond 10 percent copper. It is interesting to note, however, that the grade of nickel ranged 2.7 to 4 percent in spite of low copper contents in all the fourth cleaner concentrates (C1 4 Conc).

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 97.45%, 97.19%, and 88.99%, respectively, at 200 mesh (one-stage grind flotation), and were 96.03%, 94.72%, and 81.10%, respectively, at 65 mesh (two-stage grind flotation).

TABLE 4. EFFECT OF MESH-OF-GRIND ON AX9004

Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Cleaner - MIBC 0.06 lb/ton

Flotation Time: Rougher 10 min, Cleaner 5 min

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	23.57	6.40	2.71	96.01	93.13	23.57	6.40	2.71	96.01	93.13
		Cl 4 Tail	0.67	0.71	1.00	0.31	0.98	24.24	6.24	2.66	96.32	94.11
		Cl 3 Tail	1.50	0.53	0.48	0.51	1.05	25.74	5.91	2.54	96.83	95.16
		Cl 2 Tail	3.05	0.39	0.23	0.76	1.02	28.79	5.33	2.29	97.59	96.18
		Cl 1 Tail	6.89	0.175	0.10	0.77	1.01	35.68	4.33	1.87	98.36	97.19
		R Tail	64.32	0.04	0.03	1.64	2.81	100.00	1.57	0.69	100.00	100.00
2	65	Cl 4 Conc	24.46	6.04	2.69	95.40	93.43	24.46	6.04	0.29	95.40	93.43
		Cl 4 Tail	0.60	0.80	0.78	0.31	0.67	25.06	5.91	2.64	95.71	94.10
		Cl 3 Tail	1.46	0.52	0.48	0.49	0.99	26.52	5.62	2.53	96.20	95.06
		Cl 2 Tail	2.76	0.42	0.27	0.75	1.07	29.28	5.13	2.31	96.95	96.16
		Cl 1 Tail	7.23	0.142	0.11	0.67	1.14	36.51	4.14	1.88	97.62	97.30
		R Tail	63.49	0.058	0.03	2.38	2.70	100.00	1.55	0.70	100.00	100.00
3	100	Cl 4 Conc	19.25	6.72	2.84	94.29	89.92	19.25	6.72	2.84	94.29	89.92
		Cl 4 Tail	0.71	0.88	1.04	0.46	1.22	19.96	6.51	2.78	94.75	91.14
		Cl 3 Tail	1.21	0.81	0.81	0.71	1.61	21.17	6.19	2.66	95.46	92.75
		Cl 2 Tail	4.21	0.32	0.28	0.98	1.94	25.38	5.21	2.27	96.44	94.69
		Cl 1 Tail	14.07	0.123	0.10	1.26	2.32	39.45	3.40	1.50	97.70	97.01
		R Tail	60.55	0.052	0.03	2.30	2.99	100.00	1.37	0.61	100.00	100.00
4	200	Cl 4 Conc	17.23	8.43	3.34	95.28	88.44	17.23	8.43	3.34	95.28	88.44
		Cl 4 Tail	2.01	0.62	0.69	0.82	2.14	19.24	7.61	3.06	96.10	90.58
		Cl 3 Tail	2.80	0.42	0.49	0.77	2.10	22.04	6.70	2.74	96.87	92.68
		Cl 2 Tail	6.43	0.21	0.22	0.89	2.17	28.47	5.24	2.17	97.76	94.85
		Cl 1 Tail	17.15	0.078	0.10	0.88	2.64	45.62	3.30	1.39	98.64	97.49
		R Tail	54.38	0.038	0.03	1.36	2.51	100.00	1.52	0.65	100.00	100.00
5	Rghr 65	Regr Cl 4 C	9.39	10.38	3.96	87.44	80.06	9.39	10.38	3.96	87.44	80.06
	Regr 270	Regr Cl 4 T	0.25	3.08	2.62	0.69	1.42	9.64	10.19	3.93	88.13	81.48
		Regr Cl 3 T	0.52	2.40	2.12	1.12	2.37	10.16	9.79	3.83	89.25	83.85
		Regr Cl 2 T	1.84	1.08	0.89	1.79	3.53	12.00	8.46	3.38	91.04	87.38
		Regr Cl 1 T	9.87	0.49	0.30	4.34	6.37	21.87	4.86	1.99	95.38	93.75
		Cl Tail	8.60	0.194	0.11	1.50	2.05	30.47	3.54	1.40	96.88	95.80
		R Tail	69.53	0.05	0.028	3.12	4.20	100.00	1.12	0.46	100.00	100.00

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON AX9004

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 6	Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 23°C Rougher pH: 8.5						
Cl 4 Conc	16.13	8.40	3.08	0.25	48.05	33.76	0.96
Cl 4 Tail	1.92	0.67	0.96	0.082	44.12	26.08	-
Cl 3 Tail	3.08	0.35	0.47	0.043	41.88	24.56	-
Cl 2 Tail	5.58	0.17	0.23	0.026	35.22	18.40	-
Cl 1 Tail	20.83	0.083	0.10	0.015	26.10	11.70	-
R Tail	52.46	0.070	0.031	0.013	14.00	2.40	-
Flotation Feed	100.00	1.30	0.51	0.05	22.40	10.45	0.25
Test No. 7	Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 25°C Rougher pH: 8.45						
Regr Cl 4 C	12.89	9.66	3.40	0.27	47.33	36.35	1.19
Regr Cl 4 T	0.32	1.71	2.18	0.177	47.97	31.66	-
Regr Cl 3 T	0.71	0.92	1.50	0.128	46.60	29.68	-
Regr Cl 2 T	1.42	0.56	0.75	0.065	36.42	21.11	-
Regr Cl 1 T	9.37	0.27	0.23	0.029	33.17	18.49	-
Cl Tail	7.74	0.19	0.135	0.017	29.84	16.69	
R Tail	67.55	0.080	0.041	0.010	9.79	2.87	-
Flotation Feed	100.00	1.35	0.54	0.048	17.69	10.55	-

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON AX9004

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 6 One-stage Grind Flotation																	
Cleaner 4	16.13	8.40	3.08	0.25	48.05	33.76	93.94	85.71	73.81	31.45	47.65	83.87	0.104	0.099	0.018	20.14	7.14
Cleaner 3	18.05	7.58	2.85	0.232	47.65	32.96	94.84	88.89	76.74	34.90	52.02	81.95	0.091	0.079	0.016	19.57	6.70
Cleaner 2	21.13	6.52	2.51	0.204	46.81	31.76	95.59	91.39	79.12	40.14	58.66	78.87	0.081	0.063	0.015	18.70	6.00
Cleaner 1	26.71	5.20	2.03	0.167	44.40	28.98	96.25	93.60	81.87	48.14	67.66	73.29	0.074	0.051	0.014	17.44	5.05
Rougher	47.54	2.96	1.19	0.101	36.39	21.41	97.45	97.19	87.55	70.22	88.99	52.46	0.070	0.031	0.013	14.00	2.40
Test No. 7 Two-stage Grind Flotation																	
Regr Cleaner 4	12.89	9.66	3.40	0.27	47.33	36.35	91.62	83.24	72.50	31.89	45.72	87.11	0.131	0.101	0.015	14.96	6.39
Regr Cleaner 3	13.21	9.47	3.37	0.268	47.31	36.26	92.02	84.57	73.75	32.67	46.70	86.79	0.125	0.094	0.015	14.84	6.30
Regr Cleaner 2	13.92	9.03	3.28	0.261	47.27	35.92	92.50	86.60	75.62	34.40	48.75	86.08	0.119	0.082	0.014	14.58	6.11
Regr Cleaner 1	15.34	8.25	3.04	0.243	46.28	34.55	93.09	88.63	77.49	37.12	51.67	84.66	0.111	0.071	0.013	14.20	5.86
Cleaner	24.71	5.22	1.98	0.162	41.32	28.45	94.95	92.73	83.12	53.38	68.53	75.29	0.091	0.051	0.011	11.85	4.29
Rougher	32.45	4.02	1.54	0.127	38.58	25.64	96.03	94.72	85.83	65.46	81.10	67.55	0.080	0.041	0.010	9.74	2.87

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF AX9004

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+150	0.4	-	0.8
+200	3.1	2.2	4.3
+270	11.8	3.3	14.2
+400	27.1	18.1	33.7
-400	57.6	76.4	47.0
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	-	-	-
+65	0.3	-	0.8
+100	4.4	-	8.3
+150	28.8	-	34.2
+200	21.0	0.3	21.1
+270	12.4	0.8	9.3
+400	9.2	5.6	7.4
-400	23.9	93.3	18.9

*Cl 4 Conc and Regr Cl 4 Conc, respectively

In spite of rather high recoveries of copper and nickel, the sulfur contents in the rougher tailings were unexpectedly high, 2.40 and 2.87 percent. In the preliminary series of flotation tests this particular point was overlooked since the flotation products were analyzed only for copper and nickel and all the rougher tailings analyzed about 0.05 percent both in copper and nickel. These levels of copper and nickel in rougher tailings were as low as one could achieve in all the other samples. It was surmised that the high sulfur contents of the rougher tailings were due to unfloated iron sulfides. It was also noted as in the preliminary series of flotation tests that the flotation concentrates could not be upgraded beyond 10 percent copper both in the one-stage grind flotation and in the two-stage grind flotation even after four cleaning operations.

The sum of the copper, nickel, cobalt, iron, and sulfur contents may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The fourth cleaner concentrate (Cl 4 Conc) in the one-stage grind flotation would then have 6.5 percent gangue and the reground first cleaner concentrate (Regr Cl 4 Conc) in the two-stage grind flotation would have 3.0 percent gangue. These values of the gangue contents are notably lower than all the other samples, yet the grades of copper in flotation concentrates were surprisingly low. Such an observation would indicate that this sample contained a large amount of iron sulfides. In fact, the iron and sulfur contents of Cl 4 Conc and Regr Cl 4 Conc are seen to be very high, and also the Cl Tails and the Regr Cl Tails are seen to be high in iron and sulfur indicating that iron sulfides were

rejected more or less preferentially in the cleaner stages. The high sulfur contents of R Tails, 2.40 percent and 2.87 percent, respectively, are also in agreement with a well-known view that pyrrhotite is less floatable than copper sulfides.

A Davis magnetic tube test was performed on a Cl 4 Conc sample to explore the feasibility of a copper-nickel separation, but the magnetic concentrate amounted to only 0.08 percent by weight. Hence, chemical analyses on the magnetic separation products were not made. Evidently, the pyrrhotite in the present sample is the nonmagnetic variety.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, Cl Tail, and R Tail samples in both the one-stage grind flotation test and in the two-stage grind flotation tests were analyzed by Barringer Research Ltd. The results are given in Tables 7 and 8. In these tables it is seen that the concentration of such trace elements as tellurium and molybdenum notably increased. The amount of silver in the cleaner concentrate increased to some extent. These increases are apparently due to the close association of these elements with sulfide minerals. The copper, nickel, iron and cobalt analyses by Barringer and by the MRRC are seen to be in reasonably good agreement. The silicon analyses in Tables 7 and 8 appear to be unreasonably low since the feed and tailing samples were essentially silicates.

To relate the flotation behaviors to the mineralogical and liberation characteristics of sulfide minerals, the Regr Cl 4 Conc and the R Tail samples of the two-stage grind flotation test were screened into size fractions and the mineralogical composition of each fraction was determined

TABLE 7. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9004 (TEST 6 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	6.49		0.742		6.55		8.0	
B	0.0444		0.053		0.117		0.145	
Be	0.00012		0.00001		0.00012		0.00014	
Ca	3.43		0.336		3.31		4.2	
Cu	1.15	1.30	7.47	8.40	0.0837	0.083	0.0217	0.070
Fe	22.9	22.40	46.4	48.05	26.4	26.10	12.7	14.00
Mg	2.69		0.345		2.39		3.47	
Mn	0.111		0.0143		0.1		0.151	
P	nd		nd		nd		0.027	
Ba	0.0342		0.0044		0.0264		0.133	
Se	0.02		0.02		nd		nd	
Te	0.422		0.709		0.422		0.266	
As	nd		nd		nd		nd	
Si	0.226		0.0112		0.938		1.28	
Sr	0.0154		0.00186		0.0154		0.0193	
Zr	0.006		0.0015		0.0079		0.0095	
Ti	0.651		0.539		0.592		0.928	
V	0.0214		0.0225		0.0189		0.0294	
Zn	0.0194		0.0028		0.0169		0.025	
Th	nd		nd		nd		0.007	
K	0.746		0.045		0.744		0.962	
Na	1.2		0.218		1.31		1.62	
Cd	nd		nd		nd		nd	
Cr	0.0516		0.00308		0.0709		0.0489	
Co	0.0356	0.05	0.204	0.25	0.0066	0.015	0.0044	0.013
Ag	nd		0.0014		nd		nd	
Mo	0.0011		0.0078		0.0003		0.0007	
Ni	0.415	0.51	2.74	3.08	0.0778	0.10	0.0214	0.031
Pb	nd		nd		nd		nd	

*Conventional AA analyses

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9004 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	6.37		0.335		5.04		7.96	
B	0.0412		0.0874		0.0621		0.158	
Be	0.00012		nd		0.00009		0.00014	
Ca	3.45		0.151		2.75		4.4	
Cu	1.16	1.35	8.2	9.66	0.135	0.19	0.0336	0.080
Fe	23.4	17.69	47.6	47.33	31.5	29.84	12.4	9.79
Mg	2.69		0.162		1.96		3.28	
Mn	0.11		0.0068		0.0791		0.138	
P	nd		nd		nd		0.026	
Ba	0.0278		0.0028		0.027		0.115	
Se	nd		0.04		nd		nd	
Te	0.422		0.822		0.556		0.272	
As	nd		0.003		nd		nd	
Si	0.177		0.0112		0.332		1.32	
Sr	0.0149		0.00078		0.0121		0.0195	
Zr	0.0059		0.0012		0.0062		0.0095	
Ti	0.645		0.0251		0.468		0.846	
V	0.0212		0.00081		0.0151		0.0267	
Zn	0.0177		0.0003		0.0141		0.0207	
Th	nd		nd		nd		nd	
K	0.714		0.013		0.552		0.948	
Na	1.16		0.12		0.927		1.56	
Cd	nd		nd		nd		nd	
Cr	0.0239		nd		0.0362		0.0312	
Co	0.0363	0.048	0.22	0.27	0.009	0.017	0.0038	0.010
Ag	nd		0.0017		nd		nd	
Mo	nd		0.0089		nd		nd	
Ni	0.422	0.54	2.96	3.40	0.1	0.135	0.0175	0.041
Pb	nd		nd		nd		nd	

*Conventional AA analyses

by examining it first under transmitted light for silicate minerals and then under reflected light for opaque minerals. The results on the sized fractions are shown in Tables 9(a) and (b).

In these tables it is apparent that over 95 percent of the particles in each size fraction of the R Tail were free, and that most of the free opaques were pyrrhotite-pentlandite particles. It is also noted that, although relatively minor in proportion, the particles locked with pyrrhotite and pentlandite (Po-Pn) were more or less evenly distributed over all the size ranges, but those locked with chalcopyrite and cubanite (Cp-Cb) decreased as the particle size became finer. These observations would indicate that pyrrhotite-pentlandite particles, free or locked with gangue, are difficult to float, and also that coarse Cp-Cb/gangue particles were difficult to float. In these particles a substantial portion of chalcopyrite occurred as fine inclusions in the silicates, mostly feldspar and pyroxene. These mineralogical characteristics are in good agreement with the chemical assay results of the R Tail which were high in sulfur and iron, but low in copper and nickel.

The Cl 4 Conc, particularly in minus 400 mesh fraction which made up over 93 percent by weight of the concentrate, was estimated to consist of 50 percent or more of Po-Pn particles. Such an observation would account for the chemical assay results of the Cl 4 Conc which were relatively low in copper. That the number of locked particles was relatively low and its proportion decreased in finer size ranges are also in line with the low gangue content of the present concentrate. From these data it appears that the separation of the bulk sulfide concentrate into a copper concentrate and a nickel concentrate by differential flotation would be possible.

TABLE 9(a). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF TWO-STAGE GRIND FLOTATION (TEST 7) ON AX9004 UNDER TRANSMITTED LIGHT

Size, mesh	% Wt	Free Particles						Locked Particles		
		Opaques	Olivine	Pyroxene	Feldspar	Biotite	Others*	Op/Olivine Pyroxene	Op/Feld	Op/Others*
					(a) Rougher Tailing					
65	0.8	6.1	2.6	34.3	3.9	42.6	10.4	0.0	0.1	0.0
100	8.3	8.9	13.1	36.2	11.5	9.9	15.8	1.1	1.3	2.1
150	34.2	9.9	22.7	26.4	14.8	8.7	14.1	0.4	1.2	1.8
200	21.1	10.7	21.1	20.1	15.8	7.5	20.7	0.2	2.2	1.7
270	9.3	14.1	20.3	12.6	22.5	12.2	16.8	0.0	1.4	0.1
400	7.4	5.1	30.5	5.6	32.6	8.1	16.2	0.6	1.2	0.1
-400	18.9	-	-	-	-	-	-	-	-	-
					(b) Regr Cleaner 4 Concentrate					
200	0.3	53.8	9.1	8.3	15.1	3.5	0.4	2.3	4.7	2.8
270	0.8	56.2	8.9	8.7	14.6	2.5	0.5	2.0	4.2	2.4
400	5.6	86.8	3.5	1.1	5.0	1.7	0.6	0.0	1.3	0.0
-400	93.3	99.2	0.1	0.1	0.4	0.0	0.0	0.0	0.1	0.0

*Others: chlorite, amphibole, apatite

TABLE 9(b). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF TWO-STAGE GRIND FLOTATION (TEST 7) ON AX9004 UNDER REFLECTED LIGHT

Size, mesh	Free Particles			Locked Particles			
	Po-Pn	Cp-Cb	Ilm/Mag	Po-Pn/ Gangue	Cp-Cb/ Gangue	Ilm/Mag Gangue	Po-Pn/ Cp-Cb
			(a) Rougher Tailing				
65	70	5	25	5	25	70	tr
100	80	tr	20	10	10	80	0
150	90	0	10	15	5	80	0
200	90	0	10	20	tr	80	0
270	80	tr	20	10	tr	90	0
400	60	0	40	5	5	90	0
-400	50	0	50	10	0	90	0
			(b) Regr Cleaner 4 Concentrate				
200	25	70	5	40	60	0	tr
270	25	75	tr	50	50	0	tr
400	40	60	tr	40	60	0	tr
-400	50	50	tr	30	70	0	0

tr: trace (less than ~5%)

Cp: chalcopyrite
Cb: cubanite
Pn: pentlandite
Po: pyrrhotite
Ilm: ilmenite
Mag: magnetite

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were taken in a similar manner after one week and one month of standing, but the analyses of these solution samples for trace elements were withheld since all the other samples showed virtually identical trends. The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 10 shows the amounts of residual flotation reagents in the liquors. Tables 11 and 12 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease from near 8.3 during flotation to about 7.8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed appreciably in one week, and these reagents became virtually absent after one month. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors. The concentration of copper remained in the range of 10 to 20 ppb. The concentrations of nickel ions in the pulp solutions were essentially below the limit of detection by the analytical method used (90 ppb). Of note is the zinc-ion concentration which was at a few hundredths to a few tenths of one ppm.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of

TABLE 10. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTION OF AX9004

Sampling Time	One-stage Grind Flotation (Test 6)			Two-stage Grind Flotation (Test 7)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	8.2	0.46	5.69	8.3	0.35	7.91
After 1 Day	8.0	0.27	4.09	8.1	0.28	5.84
After 1 Week	7.9	0.20	0.00	8.0	0.23	0.22
After 1 Month	7.8	0.19	0.00	7.7	0.21	0.00

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9004 (TEST 6 - MINUS 200 MESH GRIND)

	Feed Water	Tailing Water			
		immed.	1 day old	1 week old	1 month old
Al	0.34	0.77			
B	nd	nd			
Ba	nd	nd			
Be	nd	nd			
Ca	15.9	12.7			
Cu	0.02	0.017			
Fe	0.244	0.645			
K	5.7	4.5			
Mg	4.38	2.82			
Mn	0.0378	0.0307			
Na	27	11			
P	nd	nd			
Se	nd	nd			
Te	nd	nd			
Pb	nd	nd			
Si	1.29	1.90			
Sr	0.0331	0.0238			
Ti	0.004	0.011			
V	0.004	0.005			
Zn	0.06	0.05			
Th	nd	nd			
Ag	nd	nd			
As	nd	nd			
Cd	nd	nd			
Co	nd	nd			
Cr	0.021	0.017			
Mo	nd	0.06			
Ni	nd	nd			
Zr	nd	nd			

TABLE 12. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9004 (TEST 7 - MINUS 65 MESH GRIND)

	Feed Water	Tailing Water			
		immed.	1 day old	1 week old	1 month old
Al	0.31	0.2			
B	nd	nd			
Ba	nd	nd			
Be	nd	nd			
Ca	14.5	13.0			
Cu	0.023	0.011			
Fe	0.298	0.073			
K	3.8	4.5			
Mg	2.56	2.34			
Mn	0.0272	0.0236			
Na	23	13			
P	nd	nd			
Se	nd	nd			
Te	nd	nd			
Pb	nd	nd			
Si	1.54	1.54			
Sr	0.0275	0.0266			
Ti	0.005	0.002			
V	0.005	0.004			
Zn	nd	0.15			
Th	0.013	nd			
Ag	nd	nd			
As	nd	nd			
Cd	nd	nd			
Co	nd	nd			
Cr	0.013	0.011			
Mo	0.06	0.1			
Ni	0.12	nd			
Zr	nd	nd			

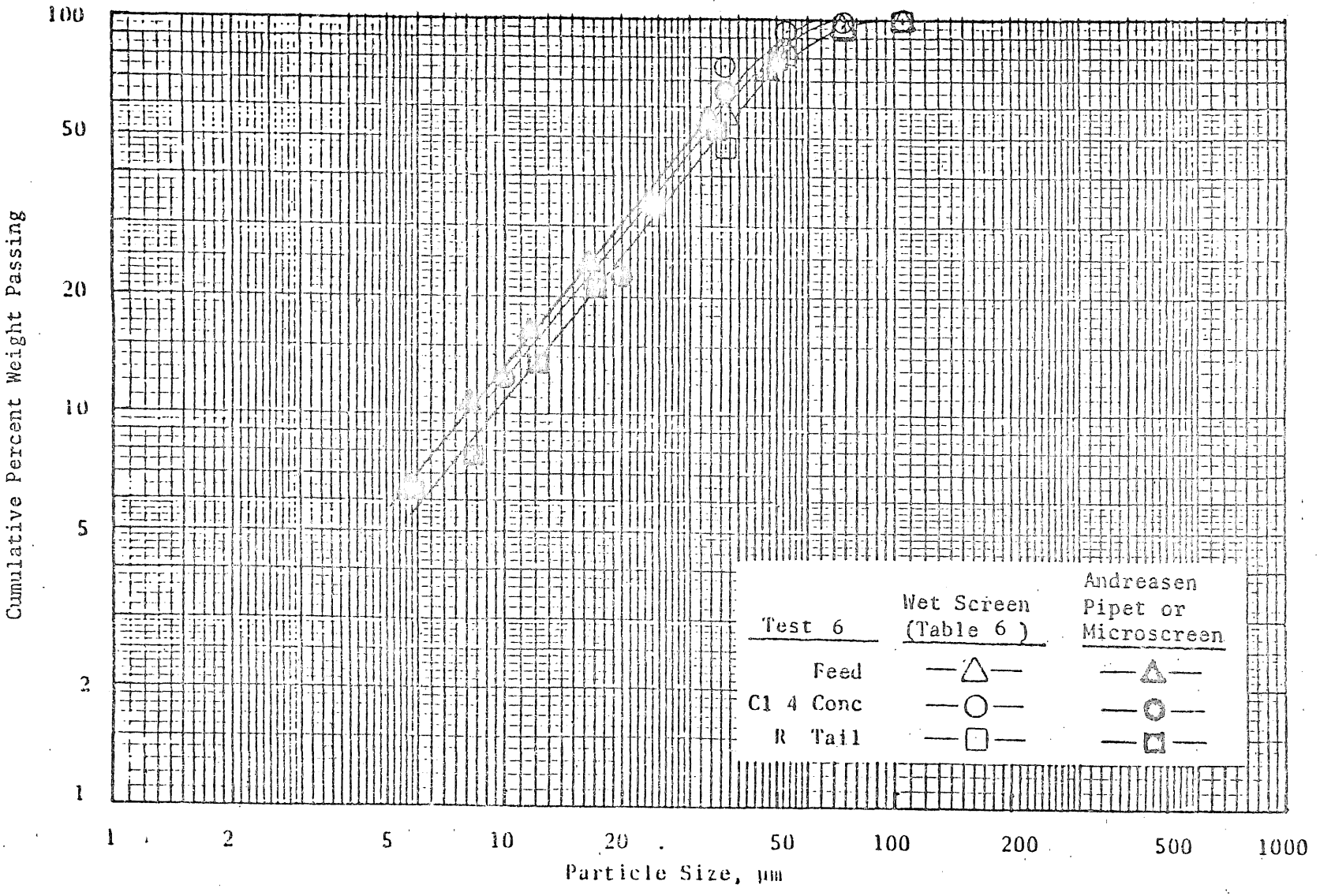


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF AX9004 (MINUS 200 MESH GRIND)

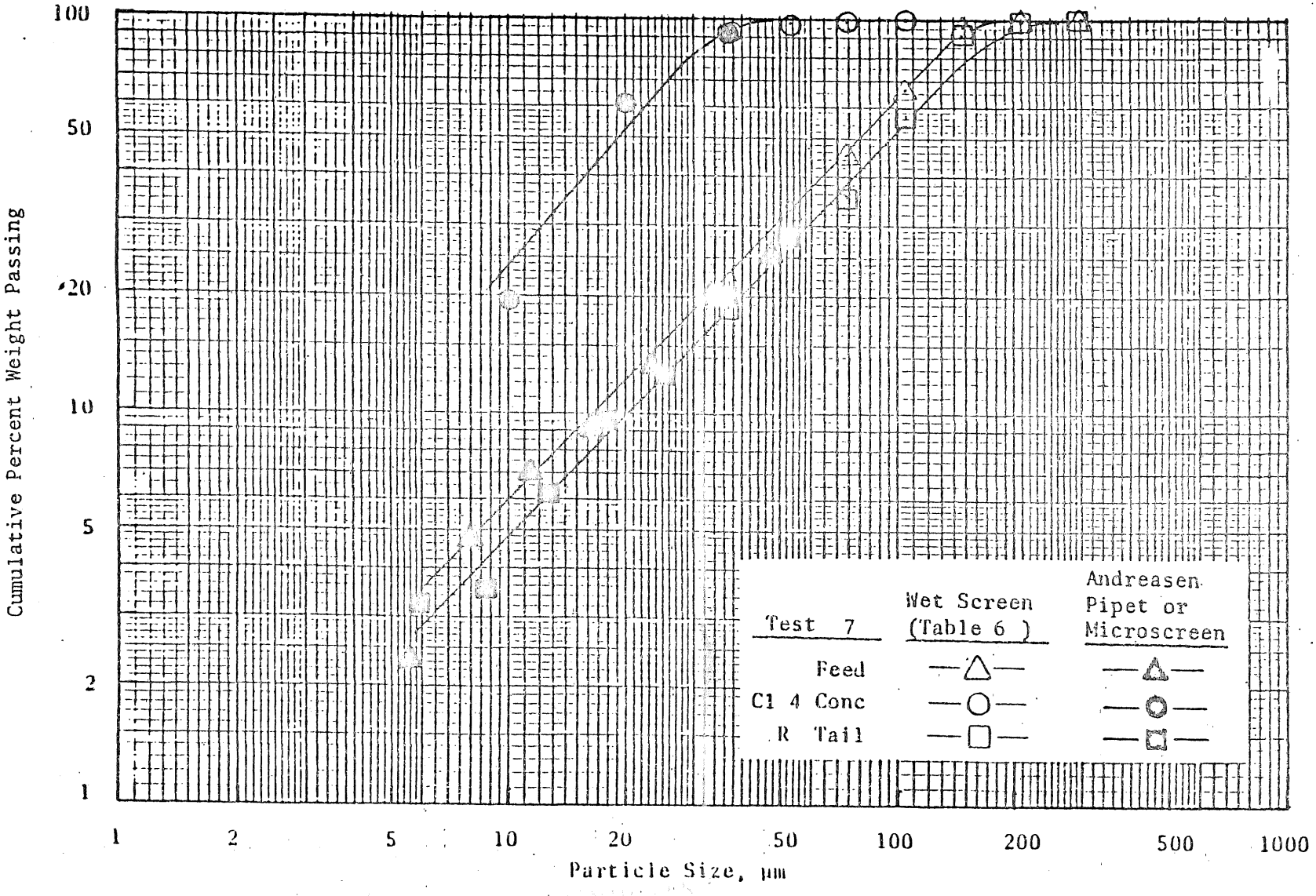


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF AX9004
(MINUS 65 MESH FOR FEED AND TAILING, MINUS 270 MESH FOR CONCENTRATE)

Table 6. The size distributions of concentrates in the same range were determined by microscreening (Table 13). The data in the 'subsieve' range are of particular interest since the air-borne dusts are said to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200-mesh grind would have about 6 percent by weight of minus 5-μm particles. At a 65-mesh grind, however, minus 5 μm particles would be about 3 percent. The above amounts of potential dust particles should be viewed with caution since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

Modified Flotation Test Results

In the preliminary series of flotation tests showing the effect of mesh-of-grind (Table 4) it was felt that the standard flotation procedures would recover all the recoverable sulfides judging from the copper and nickel analyses of rougher tailings. Hence, the standardized flotation tests were performed and the flotation products were analyzed for five elements, namely copper, nickel, cobalt, iron and sulfur. Their rougher tailings in Table 5, however, analyzed 2.40 and 2.87 percent sulfur, respectively, for the one-stage grind and the two-stage grind flotation tests. Since the rougher tailings of all the samples tested except for DP9002 and AX9004 samples analyzed in the neighborhood of 0.1 percent sulfur, the above values of 2.40 and 2.87 percent were thought to be unexpectedly high. In an attempt to recover the remaining sulfides in the rougher tailings, the effect of the stage addition of the collector was tested. For this purpose a modified flotation test procedure was

TABLE 13. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF AX9004

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	33.91	-
+20	84.22	43.28	82.45
+10	6.55	10.64	9.32
+5	3.17	12.17**	3.70
-5	6.06	-	4.53
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+37	-	7.99	-
+20	92.06	30.82	92.77
+10	3.95	41.68	3.64
+5	1.69	19.51**	1.50
-5	2.30	-	2.09

* Cl 4 Conc and Regr Cl 4 Conc, respectively
**Minus 10 µm

developed for AX9004 sample, as shown in Figures 5 and 6. In these tests larger amounts of the collector (KAX) were added in stages to insure full recoveries of sulfide minerals. The flotation results are given in Table 14, and those in the scavenger circuits are summarized in Table 15.

TABLE 15. SUMMARY OF FLOTATION RESULTS IN SCAVENGER CIRCUITS OF TESTS 13 AND 14

Test No.		Product	% Wt	% Cu	% Ni	% S
13	One-stage Grind Flotation	Sc 2 Tail	38.56	0.068	0.029	0.14
		Sc 1 Tail	44.14	0.065	0.033	0.31
14	Two-stage Grind Flotation	Sc 2 Tail	50.14	0.035	0.018	0.24
		Sc 1 Tail	53.07	0.038	0.020	0.64

It is readily apparent that the sulfur contents in the Sc 2 Tails are seen to be lowered to 0.14 to 0.24 percent with additional stages of the collector addition. The copper and nickel contents in the tailings, however, could not be lowered too much beyond those obtained under the standardized flotation test conditions (Table 5) indicating that the copper- and nickel-bearing sulfides were fully liberated at the mesh-of-grind used in these tests. The residual concentrations of the collector (KAX) in pulp solutions for the present tests were determined at several points in the modified flowsheet and the results are given in Table 16. When these results are compared with the data presented in Table 10, it is apparent that the residual xanthate concentration in excess of a few ppm might be needed to insure full recoveries of all the sulfides.

In Table 14 the copper contents of concentrates are seen to be lower than those in Table 5 which would indicate that additional pyrrhotite was recovered thereby diluting the concentrates. Apparently, the regrinding of

TABLE 14(a). MODIFIED FLOTATION TEST RESULTS ON AX9004

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Zn
Test No. 13 Grind: -200 mesh Flotation Time: Rougher and Scavenger 10 min, Cleaner 5 min							
Cl 4 Conc	27.04	4.80	2.18	0.180	56.02	34.80	0.034
Cl 4 Tail	1.01	0.28	0.42	0.050	27.29	13.56	0.035
Cl 3 Tail	2.24	0.20	0.30	0.036	26.58	12.83	0.038
Cl 2 Tail	6.58	0.11	0.18	0.024	21.54	9.20	0.031
Cl 1 Tail	18.99	0.055	0.09	0.020	12.85	3.44	0.034
Sc 2 Conc	5.58	0.051	0.057	0.015	9.72	1.50	0.054
Sc 2 Tail	38.56	0.068	0.029	0.012	7.23	0.136	0.012
Test No. 14 Grind: Rougher - 65 mesh Regr Cleaner -270 mesh Flotation Time: Rougher and Scavenger 10 min, Cleaner 5 min							
Regr Cl 4 Conc	15.58	8.02	3.30	0.26	50.81	35.64	0.043
Regr Cl 4 Tail	0.46	0.62	1.23	0.111	45.29	25.86	0.033
Regr Cl 3 Tail	0.68	0.40	0.95	0.090	41.20	23.10	0.030
Regr Cl 2 Tail	3.02	0.17	0.31	0.040	41.12	23.15	0.024
Regr Cl 1 Tail	16.00	0.075	0.13	0.020	37.59	20.14	0.025
Cl Tail	11.19	0.10	0.069	0.017	16.06	5.86	0.037
Sc 2 Conc	2.93	0.089	0.049	0.013	11.08	7.46	0.030
Sc 2 Tail	50.14	0.035	0.018	0.014	6.75	0.24	0.039

TABLE 14(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF MODIFIED FLOTATION TESTS ON AX9004

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No.13 One-stage Grind Flotation																	
Cleaner 4	27.04	4.80	2.18	0.180	56.02	34.80	96.00	91.58	77.78	65.25	83.80	72.96	0.074	0.074	0.019	11.06	2.49
Cleaner 3	28.05	4.64	2.12	0.178	55.01	34.04	96.21	92.23	79.37	66.46	85.02	71.95	0.071	0.069	0.018	10.83	2.34
Cleaner 2	30.29	4.31	1.98	0.169	52.92	32.47	96.91	93.27	80.96	69.04	87.58	69.71	0.067	0.062	0.017	10.31	2.00
Cleaner 1	36.87	3.56	1.66	0.144	47.33	28.31	97.07	95.10	84.14	75.16	92.97	63.13	0.063	0.050	0.016	9.14	1.25
Rougher + Scav 1	55.86	2.37	1.13	0.102	35.61	19.86	97.86	97.76	90.48	85.67	98.79	44.14	0.066	0.033	0.014	7.54	0.31
Test No.14 Two-stage Grind Flotation																	
Regr Cleaner 4	15.58	8.02	3.30	0.260	50.81	35.64	93.55	89.47	73.24	37.41	51.66	84.42	0.064	0.072	0.018	15.69	6.15
Regr Cleaner 3	16.04	7.81	3.24	0.256	50.69	35.36	96.07	90.46	74.14	38.40	52.77	83.96	0.061	0.065	0.017	15.53	6.04
Regr Cleaner 2	16.72	7.51	3.15	0.249	50.30	34.86	96.28	91.59	75.22	39.72	54.23	83.28	0.058	0.058	0.016	15.32	5.90
Regr Cleaner 1	19.74	6.38	2.71	0.217	48.59	33.07	96.67	93.23	77.39	45.58	60.74	80.26	0.054	0.049	0.016	14.35	5.25
Cleaner	35.74	3.56	1.56	0.129	43.82	27.28	97.59	96.85	83.18	73.97	90.73	64.26	0.049	0.028	0.015	8.58	1.55
Rougher + Scav 1	46.93	2.74	1.20	0.102	37.20	22.17	98.45	98.19	86.62	82.47	96.84	53.07	0.038	0.120	0.014	6.99	0.64

TABLE 16. RESIDUAL XANTHATE CONCENTRATIONS IN PULP SOLUTIONS OF TESTS 13 AND 14 FOR AX9004

Solution Sample	KAX, ppm	
	One-stage Grind Flotation (Test 13)	Two-stage Grind Flotation (Test 14)
Before Rougher	8.65	5.56
After Rougher	0.52	1.76
After Scavenger 1	1.21	2.34
After Scavenger 2	2.08	3.58

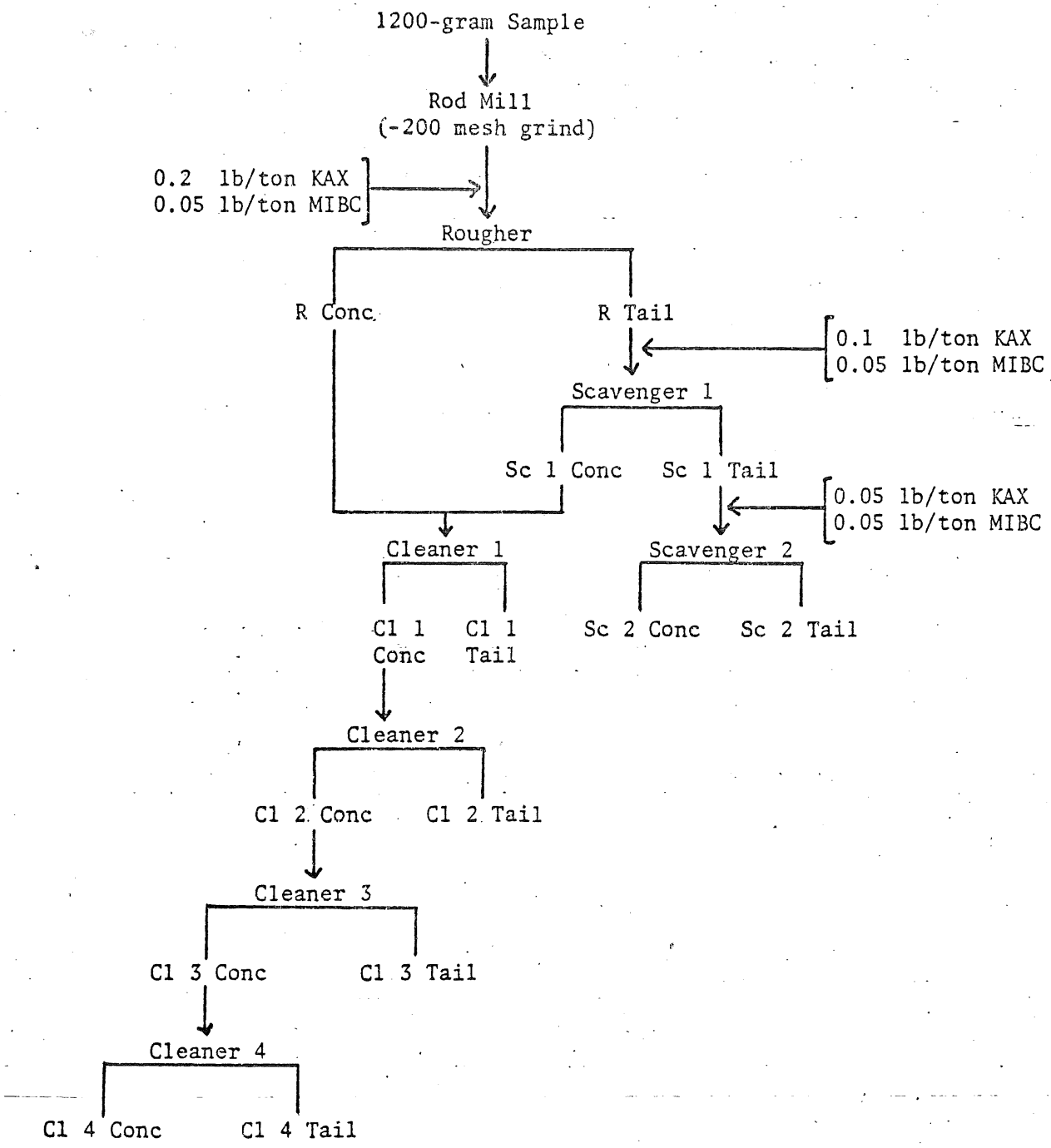


FIGURE 5. MODIFIED FLOTATION FLOWSHEET OF TEST 13 FOR AX9004

the concentrate made pyrrhotite particles less floatable and the grade of the final concentrate was higher in copper and nickel than in the one-stage grind flotation. The results of the modified flotation procedures clearly indicated that the recovery of sulfide minerals, particularly pyrrhotite, could be maximized through the stage addition of the collector, but the concentrate grade became less than 5 percent copper. It then appears that differential flotation must be considered if the concentrate grade is to be maintained above 10 percent copper. The disposal of the pyrrhotite rejected in the differential flotation step would then have to be considered.

3.9 FLOTATION TESTS ON AX9005 SAMPLE

Sample Description

An AMAX mineralized rock sample, labeled AX9005, weighing approximately 321 kilograms, was received on November 22, 1977 from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. The sample was a composite of lumps hand-picked from a 260-ton pile of MRRC Sample No. 2, which was reported to have been taken from Rounds 180 to 250 (546 to 738 feet) in the 'A' drift.

The whole sample was stage-crushed to minus 3 mesh and mixed by passing through a Jones splitter six times. Two 5-pound samples were removed at this size for archiving and for leaching studies by the Environmental Engineering Group of the Department of Civil and Mineral Engineering. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analysis of this sample is given in Table 1.

TABLE 1. HEAD ANALYSIS OF AX9005 SAMPLE

Constituent	Percent
Copper (Cu)	0.72
Nickel (Ni)	0.175
Cobalt (Co)	0.028
Iron (Fe)	12.88
Sulfur (S)	1.52
Titanium dioxide (TiO_2)	2.06
Graphite carbon (C)	0.10

Grinding Characteristics

The grinding characteristics of the crude sample were investigated by grinding 1200-gram batches of minus 10-mesh feed in a stainless steel

laboratory rod mill at 50 percent solids for various periods of time. The size distributions of the minus 10 mesh feed and of batches ground for 15, 20, 30, and 60 minutes are given in Table 2 and are plotted in Figure 1. The size distribution data of the ground batches are seen to follow straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.97. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding time of grind in Figure 2.

In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF AX9005 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50% SOLIDS)

Nominal Mesh of-grind	Grind Time Minutes	Size Modulus k, µm	80% passing µm
-10 mesh	0	-	930
-48 mesh	15	230	185
-65 mesh	20	182	147
-100 mesh	30	135	108
-200 mesh	60	74	60

Preliminary Flotation Tests

The effect of the mesh-of-grind on flotation results was investigated by grinding the minus 10-mesh sample to a nominal minus 48 mesh, minus 65 mesh, minus 100 mesh, and minus 200 mesh and by performing a standardized flotation test on each sample. Ground pulps were first conditioned in a 2-liter Denver flotation cell with 0.05 pound of KAX per ton for 2 minutes

TABLE 2. SCREEN ANALYSIS OF AX9005 AS A FUNCTION OF GRINDING TIME

Size, mesh	-10 mesh		15 Min		20 Min		30 Min		60 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+10	0.69	100.00	-	-	-	-	-	-	-	-
+14	10.99	99.31	-	-	-	-	-	-	-	-
+20	9.77	88.32	-	-	-	-	-	-	-	-
+28	22.32	78.55	-	-	-	-	-	-	-	-
+35	12.07	56.23	-	-	-	-	-	-	-	-
+48	9.53	44.16	1.08	100.00	-	-	-	-	-	-
+65	6.57	34.63	8.32	98.92	2.40	100.00	-	-	-	-
+100	6.40	28.06	22.71	90.60	15.47	97.60	1.87	100.00	-	-
+150	4.93	21.66	17.49	67.89	23.28	82.13	18.08	98.13	0.34	100.00
+200	5.73	16.73	19.07	50.40	16.50	58.85	26.44	80.05	6.37	99.66
+270	2.90	11.00	6.96	31.33	11.70	42.35	13.28	53.61	17.83	93.29
+325	1.07	8.10	3.77	24.37	6.15	30.65	5.70	40.33	12.04	75.46
+400	1.10	7.03	3.24	20.60	3.67	24.50	6.18	34.63	15.71	63.42
+500	1.53	5.93	5.18	17.36	4.83	20.83	7.31	28.45	11.73	47.71
-500	4.40	4.40	12.18	12.18	16.00	16.00	21.14	21.14	35.98	35.98

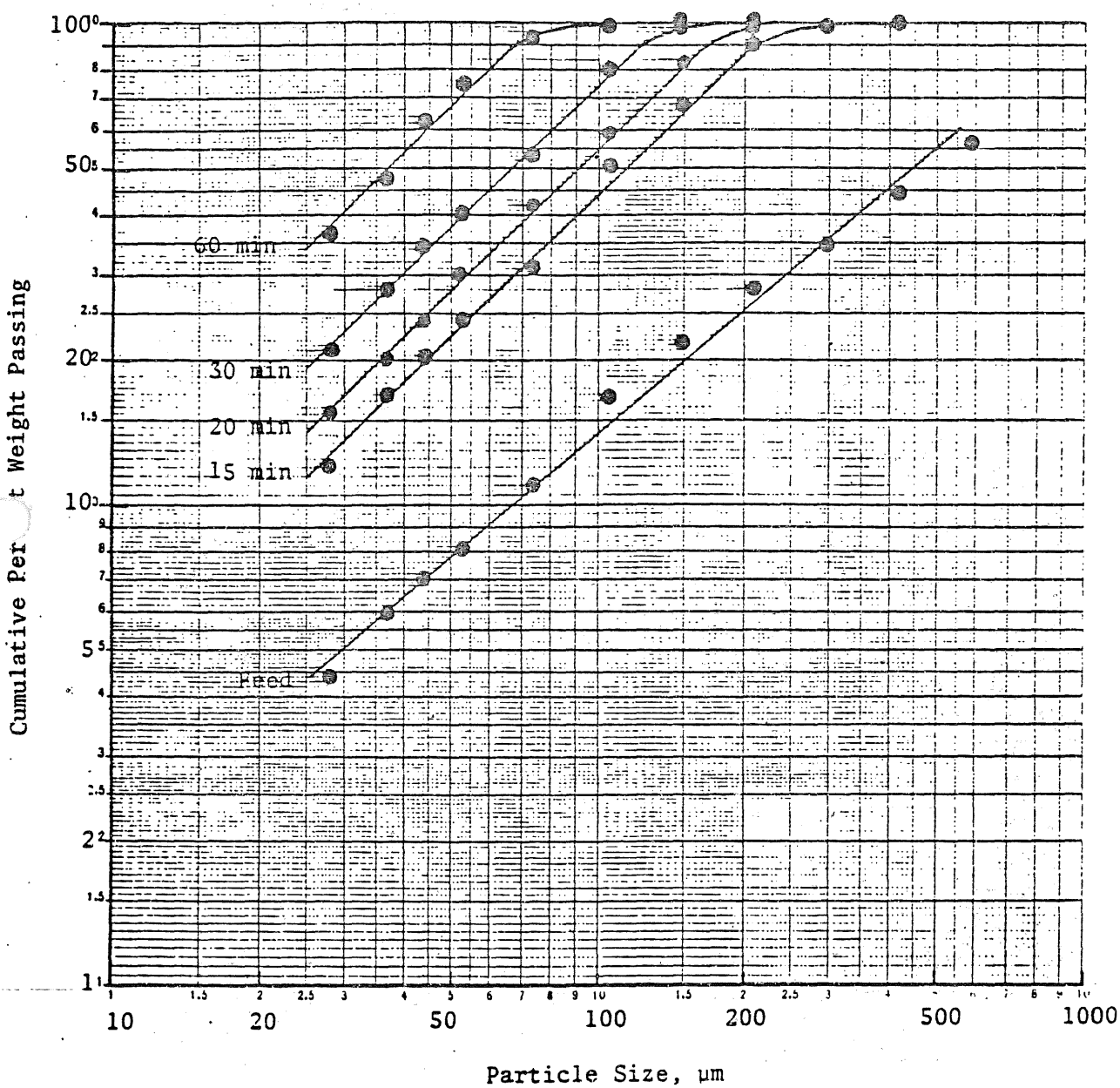


FIGURE 1. SIZE DISTRIBUTIONS OF AX9005 SAMPLE AS A FUNCTION OF GRINDING TIME

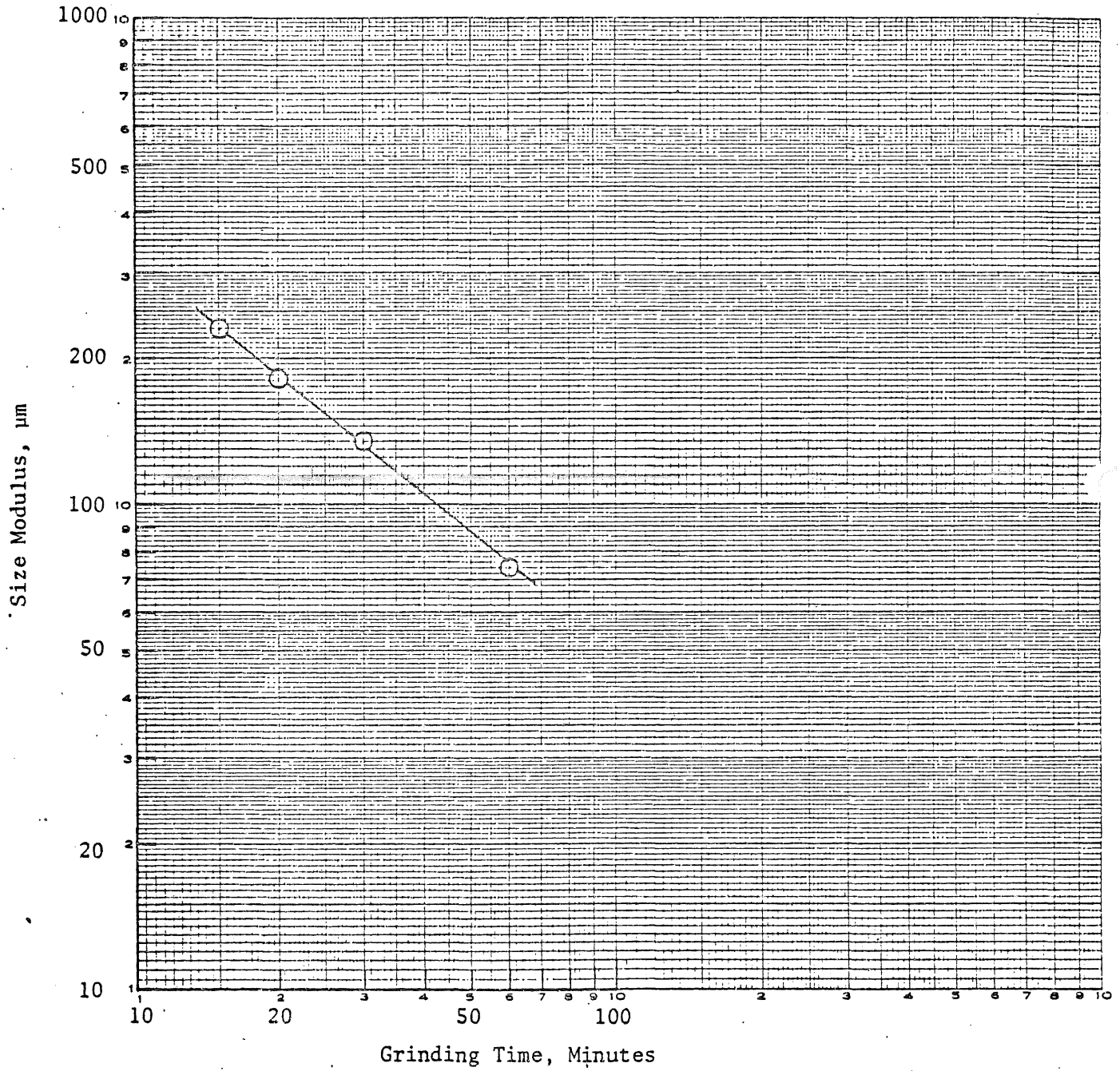


FIGURE 2. SIZE MODULI OF AX900S SAMPLE AS A FUNCTION OF GRINDING TIME

and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned successively four times. The cleaner flotation time was fixed also at 3 minutes. The results of these flotation tests are given in Table 4.

It is apparent in Table 4 that both the losses of copper and of nickel to the R Tails tended to reach plateaus at about 3 to 5 percent and 23 percent, respectively, for minus 65, 100- and 200-mesh grind samples. The loss of copper to R Tails increased noticeably at 48 mesh. It is also noted that the concentrates after three to four cleaner stages analyzed in excess of 14 percent copper and 2.6 percent nickel. In the two-stage grind flotation test a concentrate grade in excess of the above values could be achieved after two cleaner stages after regrinding.

Standardized Flotation Test Results

The results of flotation tests made according to the two standardized procedures, namely one-stage grind flotation (minus 200 mesh) and two-stage grind flotation (minus 65 mesh in rougher, minus 270 mesh in reground cleaner), are given in Table 5, and the size distributions of their flotation feed and products in Table 6. The recoveries of copper, nickel, and sulfur in the rougher flotation were 95.76%, 75.46%, and 89.89%, respectively, at 200 mesh (one-stage grind flotation), and were 89.40%, 72.85%, and 85.11%, respectively, at 65 mesh (two-stage grind flotation). The flotation concentrate could be upgraded to 14.53 percent copper and 2.38 percent nickel in the one-stage grind flotation after three cleanings, whereas in the two-stage grind flotation the concentrate was upgraded to 16.21 percent copper and 2.96

TABLE 4. EFFECT OF MESH-OF-GRIND ON AX9005
Reagents: Rougher - KAX 0.05 lb/ton, MIBC 0.05 lb/ton
Cleaner - MIBC 0.06 lb/ton
Flotation Time: Rougher 10 min, Cleaner 5 min

Test No.	Mesh-of-Grind	Product	% Wt	% Cu	% Ni	Cu Rec	Ni Rec	Cumulative % Wt	Cumulative % Cu	Cumulative % Ni	Cumulative Cu Rec	Cumulative Ni Rec
1	48	Cl 4 Conc	3.98	13.46	2.45	78.51	57.19	3.98	13.46	2.45	78.51	57.19
		Cl 4 Tail	0.46	1.40	0.80	0.94	2.17	4.44	12.21	2.28	79.45	59.36
		Cl 3 Tail	1.26	1.08	0.52	1.99	3.87	5.70	9.75	1.89	81.44	63.23
		Cl 2 Tail	1.69	0.62	0.25	1.54	2.46	7.39	7.66	1.52	82.98	65.69
		Cl 1 Tail	4.73	0.13	0.103	0.91	2.87	12.12	4.72	0.97	83.89	68.56
		R Tail	87.88	0.125	0.061	16.11	31.44	100.00	0.68	0.17	100.00	100.00
2	65	Cl 4 Conc	4.61	14.00	2.60	88.44	63.00	4.61	14.00	2.00	88.44	63.00
		Cl 4 Tail	0.55	1.59	1.05	1.21	3.05	5.16	12.68	2.43	89.65	66.05
		Cl 3 Tail	1.01	1.04	0.58	1.44	3.10	6.17	10.77	2.13	91.09	69.15
		Cl 2 Tail	1.68	0.60	0.29	1.38	2.58	7.85	8.60	1.74	92.47	71.73
		Cl 1 Tail	6.60	0.118	0.102	1.07	3.52	14.45	4.72	0.99	93.54	75.25
		R Tail	85.55	0.055	0.055	6.46	24.75	100.00	0.73	0.19	100.00	100.00
3	100	Cl 4 Conc	4.77	14.00	2.72	90.10	65.90	4.77	14.00	2.72	90.10	65.90
		Cl 4 Tail	0.46	1.28	1.10	0.80	2.59	5.23	12.88	2.58	90.90	68.49
		Cl 3 Tail	0.74	0.89	0.54	0.89	2.03	5.97	11.40	2.32	91.79	70.52
		Cl 2 Tail	1.86	0.50	0.25	1.26	2.39	7.83	8.81	1.83	93.05	72.91
		Cl 1 Tail	8.26	0.118	0.086	1.28	3.61	16.09	4.35	0.94	94.33	76.52
		R Tail	83.91	0.050	0.055	5.67	23.48	100.00	0.74	0.20	100.00	100.00
4	200	Cl 4 Conc	3.93	17.66	3.00	93.22	59.78	3.93	17.66	3.00	93.22	59.78
		Cl 4 Tail	0.59	0.92	1.38	0.73	4.11	4.52	15.47	2.79	93.95	63.89
		Cl 3 Tail	1.34	0.61	0.77	1.10	5.22	5.86	12.08	2.33	95.05	69.11
		Cl 2 Tail	3.43	0.13	0.16	0.60	2.79	9.29	7.67	1.53	95.65	71.90
		Cl 1 Tail	13.80	0.067	0.078	1.25	5.48	23.09	3.12	0.66	96.90	77.38
		R Tail	76.91	0.030	0.058	3.10	22.62	100.00	0.75	0.20	100.00	100.00
5	Rghr 65 Regr 270	Regr Cl 4 C	3.29	18.08	3.38	86.81	59.88	3.29	18.08	3.38	86.81	59.88
		Regr Cl 4 T	0.20	1.55	1.67	0.49	1.93	3.49	15.78	3.03	87.30	61.81
		Regr Cl 3 T	0.35	1.12	1.00	0.62	2.05	3.84	14.44	2.84	87.92	63.86
		Regr Cl 2 T	0.77	0.59	0.30	0.71	1.35	4.61	12.13	2.42	88.63	65.21
		Regr Cl 1 T	3.63	0.28	0.125	1.62	2.63	8.24	6.91	1.41	90.25	67.84
		Cl Tail	5.86	0.17	0.089	1.59	3.04	14.10	4.11	0.86	91.84	70.88
		R Tail	85.90	0.060	0.058	8.16	29.12	100.00	0.63	0.17	100.00	100.00

TABLE 5(a). STANDARDIZED FLOTATION TEST RESULTS ON AX9005

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 6	Grind: -200 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 23°C Rougher pH: 9.1						
Cl 4 Conc	3.39	17.60	2.52	0.161	34.42	28.86	0.62
Cl 4 Tail	0.78	1.19	1.79	0.122	19.41	8.38	-
Cl 3 Tail	1.30	0.50	0.58	0.049	15.02	3.83	-
Cl 2 Tail	3.89	0.18	0.155	0.024	14.75	2.07	-
Cl 1 Tail	15.08	0.086	0.069	0.016	12.25	0.71	-
R Tail	75.56	0.037	0.053	0.015	12.50	0.19	-
Flotation Feed	100.00	0.73	0.183	0.025	14.05	1.64	0.15
Test No. 7	Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Pulp Temperature: 25°C Rougher pH: 8.8						
Regr Cl 4 C	2.99	19.99	3.36	0.174	25.88	29.30	0.70
Regr Cl 4 T	0.11	2.58	3.46	0.196	36.20	12.84	-
Regr Cl 3 T	0.15	1.44	1.72	0.100	19.60	8.01	-
Regr Cl 2 T	0.49	0.72	0.75	0.048	16.05	5.59	-
Regr Cl 1 T	3.96	0.70	0.27	0.022	15.58	5.78	-
Cl Tail	6.25	0.19	0.090	0.015	11.56	1.13	-
R Tail	86.05	0.089	0.050	0.014	11.48	0.25	-
Flotation Feed	100.00	0.70	0.166	0.019	14.10	0.104	0.104

TABLE 5(b). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON AX9005

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 6 One-stage Grind Flotation																	
Cleaner 4	3.39	17.60	2.52	0.161	34.42	28.86	90.34	52.26	25.35	8.74	68.63	96.61	0.066	0.081	0.017	12.65	0.46
Cleaner 3	4.17	14.53	2.38	0.156	31.66	25.01	91.75	60.83	29.96	9.86	73.19	95.83	0.057	0.067	0.016	12.60	0.40
Cleaner 2	5.47	11.96	1.95	0.130	27.79	19.98	92.73	65.42	32.73	11.35	76.70	94.53	0.051	0.060	0.015	12.56	0.35
Cleaner 1	9.36	6.62	1.21	0.086	22.33	12.54	93.79	69.09	36.88	15.61	82.38	90.64	0.045	0.056	0.015	12.47	0.28
Rougher	24.44	2.59	0.51	0.043	16.12	5.24	95.76	75.46	47.94	29.43	89.89	75.56	0.037	0.053	0.015	12.50	0.19
Test No. 7 Two-stage Grind Flotation																	
Regr Cleaner 4	2.99	19.99	3.36	0.174	25.58	29.30	82.74	57.69	26.38	6.34	60.66	97.01	0.129	0.076	0.015	11.72	0.59
Regr Cleaner 3	3.10	19.37	3.37	0.174	26.13	28.71	83.13	59.87	27.40	6.67	61.63	96.90	0.126	0.072	0.015	11.69	0.57
Regr Cleaner 2	3.25	18.55	3.29	0.172	25.85	27.75	83.44	61.36	28.42	6.92	62.46	96.75	0.124	0.070	0.015	11.68	0.56
Regr Cleaner 1	3.74	16.21	2.96	0.155	24.60	24.84	83.92	63.50	29.44	7.58	64.33	96.26	0.121	0.060	0.014	11.66	0.54
Cleaner	7.70	8.23	1.58	0.087	20.00	15.04	87.75	69.64	34.01	12.69	80.19	92.30	0.096	0.057	0.014	11.48	0.31
Rougher	13.95	4.63	0.910	0.055	16.20	8.81	89.40	72.85	38.58	18.62	85.11	86.05	0.089	0.055	0.014	11.48	0.25

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF AX9005

Size, mesh	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+150	2.6	-	2.9
+200	13.0	4.4	17.4
+270	27.3	11.4	27.0
+400	13.8	20.2	14.3
-400	43.3	64.0	38.4
	(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)		
+48	0.5	-	0.2
+65	7.0	-	5.4
+100	22.1	-	20.9
+150	19.0	-	22.6
+200	17.8	-	19.6
+270	7.0	4.7	10.0
+400	6.1	7.0	5.6
-400	20.3	88.3	15.7

*Cl 4 Conc and Regr Cl 4 Conc, respectively

percent nickel after one cleaning following regrinding. The sum of the copper, nickel, cobalt, iron, and sulfur contents may be assumed to represent much of the sulfide minerals in the flotation concentrates and hence the balance would be the siliceous gangue and oxides. The third cleaner concentrate (Cl 3 Conc) in the one-stage grind flotation would then have 26.3 percent gangue and the reground first cleaner concentrate (Regr Cl 1 Conc) in the two-stage grind flotation would have 31.2 percent gangue.

A Davis magnetic tube test was performed on a Cl 4 Conc sample to explore the feasibility of a copper-nickel separation, but the magnetic concentrate amounted to only 0.69 percent by weight. Hence, chemical analyses on the magnetic separation products were not made. Evidently, the pyrrhotite in the present sample is the nonmagnetic variety.

To investigate the liberation characteristics of sulfide minerals, the fourth cleaner concentrate (Cl 4 Conc) and rougher tailing (R Tail) samples were screened into size fractions and the mineralogical composition of each fraction was determined by examining it first under transmitted light for silicate minerals and then under reflected light for opaque minerals. The results on the sized fractions from the one-stage grind flotation are shown in Table 7(a) and (b). In the R Tail the number of opaque minerals locked with silicates was small, but free opaque particles were observed to contain up to 10 percent pyrrhotite. Insufficient recovery of free pyrrhotite particles rather than locked sulfides would then account for the relatively high sulfur content (0.19%) in R Tail. In Cl 4 Conc the number of opaque minerals locked with silicates was rather high, particularly in the plus 270-mesh fractions, and these locked particles

TABLE 7(a). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF ONE-STAGE GRIND FLOTATION (TEST 6) ON AX9005 UNDER TRANSMITTED LIGHT

Size, mesh	% Wt	Free Particles						Locked Particles		
		Opaques	Olivine	Pyroxene	Feldspar	Biotite	Others*	Op/Olivine Pyroxene	Op/Feld	Op/Others*
					(a) R Tail					
150	2.9	3.2	7.4	25.5	35.4	19.2	6.6	0.5	1.2	1.0
200	17.4	3.3	12.3	25.0	47.9	6.9	2.7	0.4	1.0	0.4
270	27.0	7.3	16.0	17.0	48.7	2.6	6.2	0.0	1.2	1.0
400	14.3	10.4	26.1	8.7	50.2	0.9	2.0	0.4	0.9	0.4
-400	38.4	11.7	21.3	4.7	52.4	2.3	5.2	0.2	1.4	0.8
					(b) Cl 4 Conc					
200	4.4	48.9	0.9	2.8	21.8	1.3	1.8	2.6	17.3	2.6
270	11.4	59.1	1.0	2.0	16.2	0.2	1.4	1.9	17.9	0.3
400	20.2	71.6	0.5	2.0	12.4	0.7	0.0	2.9	7.9	2.0
-400	64.0	85.4	0.9	0.5	9.0	1.5	0.5	1.0	1.2	0.0

*Others: chlorite, amphibole, apatite

TABLE 7(b). GRAIN DISTRIBUTION DATA ON FLOTATION PRODUCTS OF ONE-STAGE GRIND FLOTATION (TEST 6) ON AX9005 UNDER REFLECTED LIGHT

Size, mesh	Free Particles			Locked Particles				
	Po-Pn	Cp-Cb	Ilm/Mag	Po-Pn/ Gangue	Cp-Cb/ Gangue	Ilmenite/ Gangue	Magnetite/ Gangue	Po-Pn/ Cp-Cb
				(a) R Tail				
150	tr	tr	100	10	10	10	70	0
200	10	tr	90	5	tr	5	90	0
270	15	tr	85	5	tr	5	90	tr
400	10	tr	90	tr	tr	tr	100	tr
-400	10	tr	90	tr	tr	tr	100	tr
				(b) C1 4 Conc				
200*	50	45	5	10	85	0	tr	5
270*	65	35	tr	20	70	0	tr	10
400*	50	45	tr	5	90	tr	tr	5
-400*	35	65	tr	tr	100	0	0	tr

tr: trace (less than ~5%)
* trace bornite

Cp: chalcopyrite
Cb: cubanite

Pn: pentlandite
Po: pyrrhotite

Ilm: ilmenite
Mag: magnetite

were mainly Cp-Cb/gangue. It is also noted that Po-Pn particles and Cp-Cb particles, whether free or locked, were well-liberated from each other over all the size ranges and particularly in the minus 400-mesh fraction, indicating the feasibility of copper-nickel separation by differential flotation.

To explore the possibility of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates, the Feed, Cl 4 Conc, Cl Tail, and R Tail samples in both the one-stage grind flotation test and in the two-stage grind flotation test were set aside, but only the Feed samples were analyzed by Barringer Research Ltd. The results are given in Tables 8 and 9. In these tables it is seen that the types and concentrations of trace elements in the present sample were within the same ranges as the other Duluth gabbro samples. The copper, nickel, iron and cobalt analyses by Barringer and by the MRRC are seen to be in reasonably good agreement. The silicon analyses in Tables 8 and 9 appear to be unreasonably low since the feed and tailing samples were essentially silicates.

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids and then were analyzed for residual flotation reagents and trace elements. Then the rougher tailing pulps were transferred to 2-liter pyrex beakers and left standing in an attempt to simulate the effect of tailings on the quality of the water in a tailing pond. The pulp solutions were taken in a similar manner after one week and one month of standing, but the analyses of these solution samples for trace elements were withheld since all the other samples showed virtually identical trends.

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9005 (TEST 6 - ONE-STAGE GRIND FLOTATION)

	Feed (-200 mesh)		Concentrate (-200 mesh)		Cleaner Tailing (-200 mesh)		Rougher Tailing (-200 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.38							
B	nd							
Be	0.00011							
Ca	5.19							
Cu	0.778	0.73						
Fe	13.3	14.05						
Mg	5.1							
Mn	0.141							
P	nd							
Ba	0.0611							
Se								
Te								
As	nd							
Si	2.56							
Sr	0.028							
Zr	0.0148							
Ti	1.26							
V	0.0208							
Zn	0.0131							
Th	0.00068							
K	0.651							
Na	2.27							
Cd	nd							
Cr	0.0312							
Co	0.0157	0.025						
Ag	0.00044							
Mo	0.0008							
Ni	0.158	0.183						
Pb	nd							
Hg**								

* Conventional AA analyses
**0.0000001% = 1 ppb

TABLE 9. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9005 (TEST 7 - TWO-STAGE GRIND FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	8.56							
B	nd							
Be	0.0011							
Ca	5.27							
Cu	0.738	0.70						
Fe	12.8	14.10						
Mg	5.03							
Mn	0.139							
P	nd							
Ba	0.0761							
Se								
T								
	nd							
Si	2.69							
Sr	0.0292							
Zr	0.0145							
Ti	1.22							
V	0.0207							
Zn	0.0119							
Th	0.00066							
K	0.697							
Na	2.3							
Cd	nd							
Cr	0.0154							
Co	0.0147	0.019						
Ag	0.00038							
Mo	nd							
Ni	0.142	0.166						
Pb	nd							
,g**								

* Conventional AA analyses
**0.0000001% = 1 ppb

The tailings were then filtered, sealed in plastic bags wet, and delivered to the Copper-Nickel Study for germination study.

Table 10 shows the amounts of residual flotation reagents in the liquors. Tables 11 and 12 present the trace element analyses done by Barringer Research Ltd. The pulp pH showed a tendency to decrease somewhat from near 8.5 immediately after flotation to about 8 in a month. Both the collector (KAX) and the frother (MIBC) decomposed almost completely in one week. The trace element analyses of the pulp solutions showed very little unusual elements appearing in pulp liquors. Of note in Table 11 is the unusually high concentration of copper ion in the tail water after one day (0.225 ppm). Perhaps this analytical result was in error, particularly because of many other data on the other samples. Further analyses of the one-week old and one-month old solutions are needed to check this point. The concentration of nickel remained below the limit of detection (90 ppb). The zinc-ion concentration amounted to a few tenths to a few ppm. Perhaps the zinc ions might have been released by the exchange reaction with copper and nickel ions.

The size distributions in the 'subsieve' range of the feeds and rougher tailings were determined by the Andreasen pipette method and the results are plotted in Figures 3 and 4 together with the wet screen results of Table 6. The size distributions of concentrates in the same range were determined by microscreening (Table 13). The data in the 'subsieve' range are of particular interest since the air-borne dusts are said to be typically in the range of 5 μm or less. From Figure 3 it is estimated that the R Tail sample at a 200-mesh grind would have about 4.5 percent by weight of minus 5-μm particles. At a 65-mesh grind, however, minus 5 μm particles would be about 1.5 percent. The above amounts of potential dust particles should be viewed with caution

TABLE 10. RESIDUAL FLOTATION REAGENTS IN TAILING PULP SOLUTION OF AX9005

Sampling Time	One-stage Grind Flotation (Test 6)			Two-stage Grind Flotation (Test 7)		
	pH	KAX ppm	MIBC ppm	pH	KAX ppm	MIBC ppm
Immediately After	8.5	0.84	3.29	8.5	1.16	2.30
After 1 Day	8.3	0.42	1.41	8.0	0.67	2.15
After 1 Week	7.9	0.21	0.0	7.9	0.23	0.0
After 1 Month	7.8	0.16	0.0	8.0	0.17	0.0

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9005 (TEST 6 - MINUS 200 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		0.41	0.46	0.11		
B		nd	nd	nd		
Ba		nd	nd	nd		
Be		nd	nd	nd		
Ca		15.6	10.3	3.52		
Cu		0.017	0.017	0.225		
Fe		0.263	0.342	0.157		
K		nd	nd	nd		
Mg		6.99	4.51	0.17		
Mn		nd	nd	0.08		
Na		29	9	nd		
P		nd	nd	nd		
Se		nd	nd	nd		
Te		nd	nd	nd		
Pb		nd	nd	nd		
Si		2.07	1.93	0.029		
Sr		0.045	0.025	0.001		
Ti		nd	nd	nd		
V		nd	nd	nd		
Zn		nd	0.36	1.16		
Th		nd	nd	nd		
Ag		nd	nd	nd		
As		nd	nd	nd		
Cd		nd	nd	nd		
Co		nd	nd	nd		
Cr		nd	nd	nd		
Mo		nd	nd	nd		
Ni		nd	nd	nd		
Zr		nd	nd	nd		

TABLE 12. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9005 (TEST 7 - MINUS 65 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		0.37	0.46			
B		nd	nd			
Ba		nd	nd			
Be		nd	nd			
Ca		9.61	9.77			
Cu		0.007	nd			
Fe		0.081	0.385			
K		nd	nd			
Mg		3.30	4.03			
Mn		nd	nd			
Na		23	8			
P		nd	nd			
Se		nd	nd			
Te		nd	nd			
Pb		nd	nd			
Si		1.68	1.88			
Sr		0.030	0.028			
Ti		nd	0.003			
V		nd	nd			
Zn		0.19	0.12			
Th		nd	nd			
Ag		nd	nd			
As		nd	nd			
Cd		nd	nd			
Co		nd	nd			
Cr		nd	nd			
Mo		nd	nd			
Ni		nd	nd			
Zr		nd	nd			

TABLE 13. SUBSIEVE SIZING RESULTS ON FLOTATION PRODUCTS OF AX9005

Size, µm	Feed % Wt	Concentrate* % Wt	R Tail % Wt
	(a) Test 6 - One-stage Grind Flotation (Minus 200 mesh)		
+37	-	38.76	-
+20	86.53	23.62	90.26
+10	6.43	14.83	5.59
+5	2.98	22.79**	2.29
-5	4.06	-	1.86
(b) Test 7 - Two-stage Grind Flotation (Minus 65 mesh in rougher, minus 270 mesh in cleaner)			
+37	-	8.64	-
+20	90.27	20.12	94.28
+10	4.59	12.98	2.42
+5	2.88	58.26**	1.71
-5	2.26	-	1.59

* Cl 4 Conc and Regr Cl 4 Conc, respectively
**Minus 10 µm

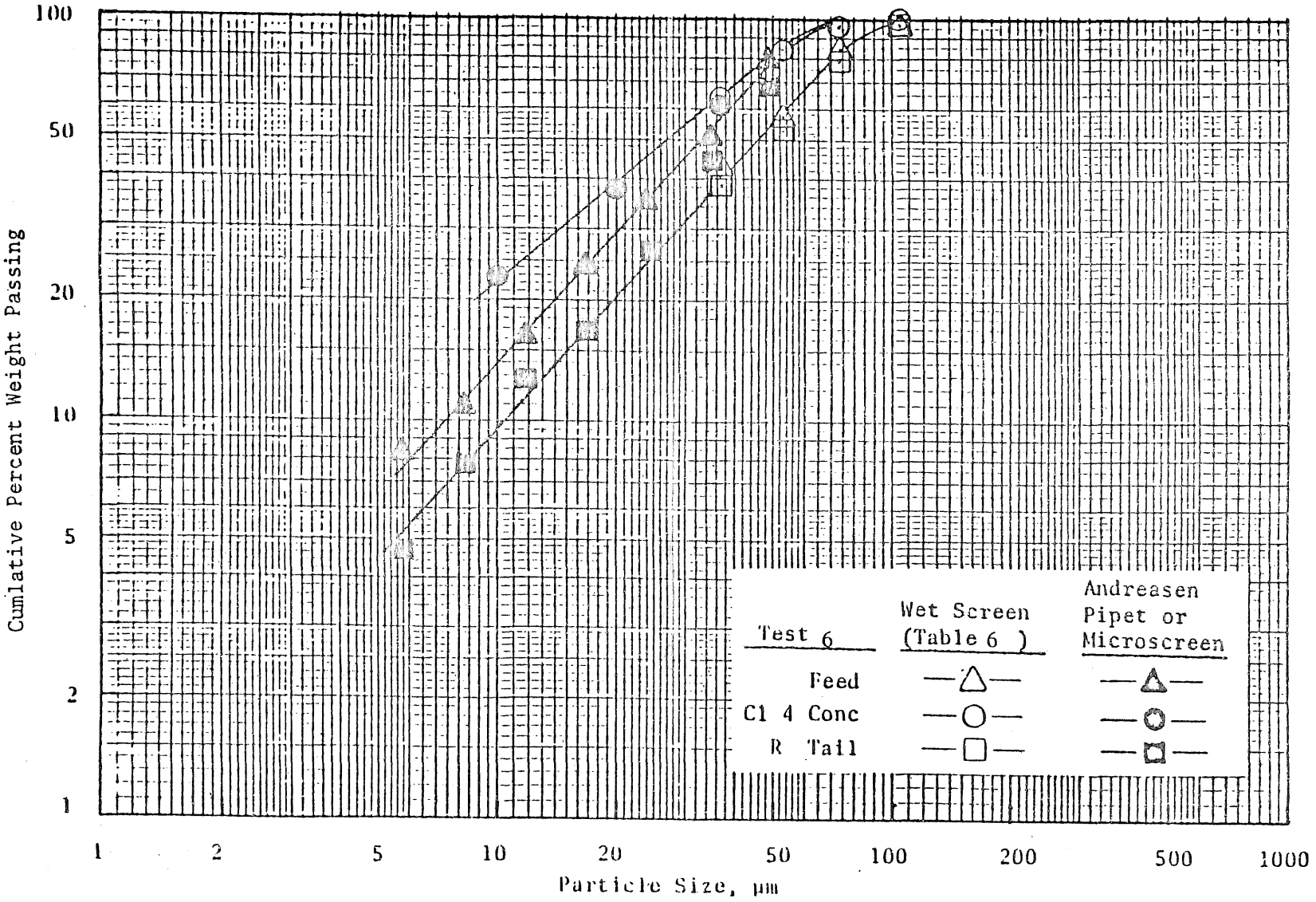


FIGURE 3. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILINGS SAMPLES IN THE ONE-STAGE GRIND FLOTATION OF AX9005 (MINUS 200 MESH GRIND)

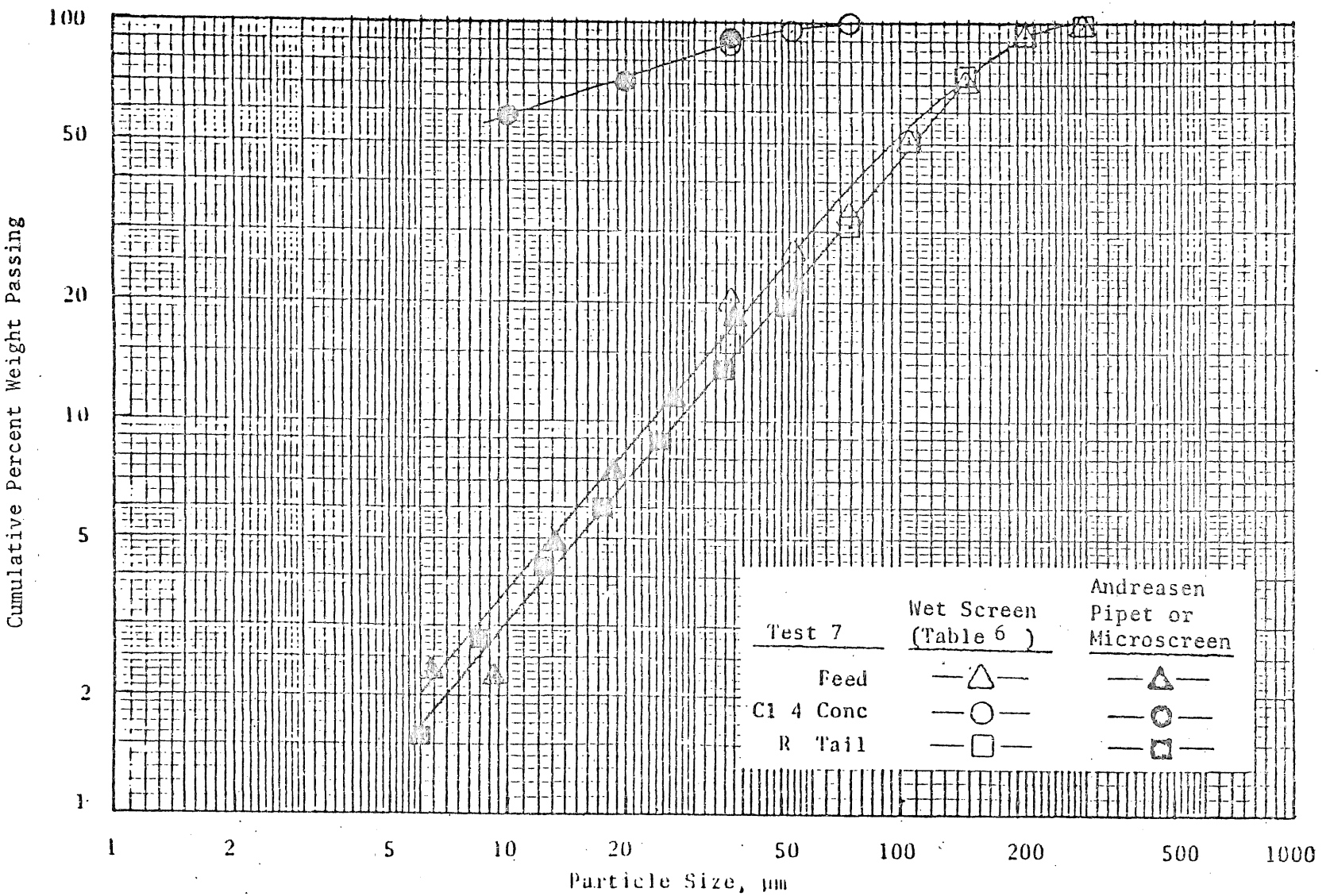


FIGURE 4. SIZE DISTRIBUTIONS OF FEED, CONCENTRATE AND TAILING SAMPLES IN THE TWO-STAGE GRIND FLOTATION OF AX9005
(MINUS 65 MESH FOR FEED AND TAILING, MINUS 270 MESH FOR CONCENTRATE)

since the slope of the size distribution lines, or the distribution moduli (m), could vary from sample to sample, and also with the type and size of grinding mills.

3.10 FLOTATION TESTS ON AX9006 AND AX9007 SAMPLES

Sample Descriptions

Two AMAX mineralized rock samples, labeled AX9006 and AX9007, weighing approximately 18 kilograms each, were received on January 31, 1978, from Mr. Robert J. Stevenson of the Department of Geology and Geophysics. These semi-massive, mineralized rock samples were added to the present study since the other semi-massive sample, AX9004, was unexpectedly low in copper. From the x-ray diffraction analyses it was found that the AX9006 sample was chalcopyrite-rich, whereas the AX9007 sample was cubanite-rich. Therefore, these two samples were tested separately rather than combined into one sample.

Each sample was stage-crushed to minus 3 mesh and then mixed by passing it through a Jones splitter six times. The minus 3-mesh material was further crushed to minus 10 mesh, mixed, and split into 1200-gram lots. The head analyses of the two samples are given in Table 1.

TABLE 1. HEAD ANALYSES OF AX9006 AND AX9007 SAMPLES

Constituent	Chemical Composition, Percent AX9006	AX9007
Copper (Cu)	6.38	3.20
Nickel (Ni)	0.505	0.228
Cobalt (Co)	0.050	0.027
Iron (Fe)	11.86	7.42
Sulfur (S)	8.32	3.42
Graphite carbon (C)	0.44	0.36

Grinding Characteristics

The grinding characteristics of the AX9006 and AX9007 samples were briefly investigated by grinding 1200-gram batches of minus 10-mesh feed

in a stainless steel laboratory rod mill at 50 percent solids for 20 and 30 minutes. The size distributions of the ground samples are given in Table 2 and are plotted in Figure 1. The size distribution data of the ground batches are seen to be represented by straight lines which are parallel to each other. The distribution modulus, m, in the Schuhmann equation, corresponding to the slope of these lines, is calculated to be 0.94. The size moduli, k, obtained by extrapolating these lines to 100 percent, are plotted against the corresponding times of grind in Figure 2. In Table 3 the nominal mesh-of-grind, the grinding time, the size modulus, and the 80 percent passing size are summarized.

TABLE 3. BATCH GRINDING CHARACTERISTICS OF AX9006 AND AX9007 IN A LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50 PERCENT SOLIDS)

Nominal Mesh-of-Grind	Grind Time, Minutes	AX9006		AX9007	
		Size Modulus k, μm	80% passing μm	Size Modulus k, μm	80% passing μm
-65 mesh	20	185	150	185	150
-100 mesh	30	108	73	118	82

Standardized and Modified Flotation Test Results

Only two-stage grind flotation tests were performed on the samples following the standardized and modified flowsheets in order to provide the metallurgical results, the size distributions of the flotation feed and product samples, the trace element analyses of the solid and water samples before and after flotation, and the tailing samples for environmental leaching studies. Other data, routinely obtained on all previous samples, were not taken in these tests, namely KAX and MIBC analyses,

TABLE 2. SIZE DISTRIBUTION OF CRUDE SAMPLE GROUND IN LABORATORY STAINLESS STEEL ROD MILL (SAMPLE WEIGHT: 1200 GRAMS AT 50 PERCENT SOLIDS)

Size, mesh	AX9006				AX9007			
	20 Min		30 Min		20 Min		30 Min	
	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum	% Wt	% Wt Cum
+65	1.41	100.00			0.98	100.00		
+100	18.85	98.59	0.45	100.00	21.08	99.02	0.59	100.00
+150	25.27	79.74	3.24	99.55	21.62	88.94	5.41	99.41
+200	12.67	54.47	27.84	96.31	14.57	56.32	34.10	94.00
+270	9.53	41.80	17.14	68.47	11.07	41.75	15.02	59.90
+325	5.18	32.27	9.15	51.33	4.12	30.68	8.09	44.88
+400	5.04	27.09	4.13	42.18	5.71	26.56	4.44	36.79
+500	6.22	22.05	11.77	38.05	5.15	20.85	8.90	32.35
-500	15.83	15.83	26.28	26.28	15.70	15.70	23.45	23.45

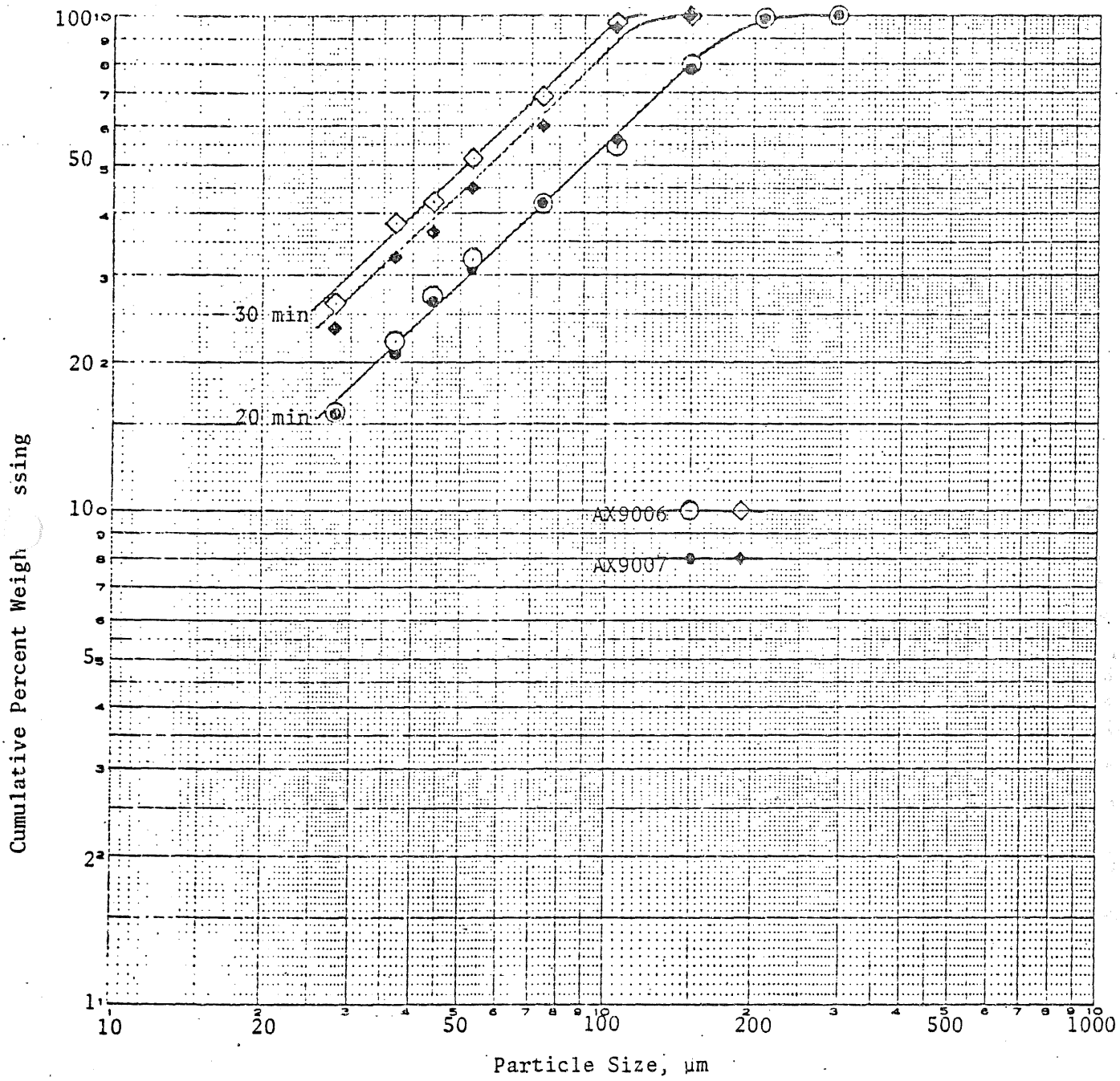


FIGURE 1. SIZE DISTRIBUTIONS OF AX9006 AND AX9007 SAMPLES AS A FUNCTION OF GRINDING TIME

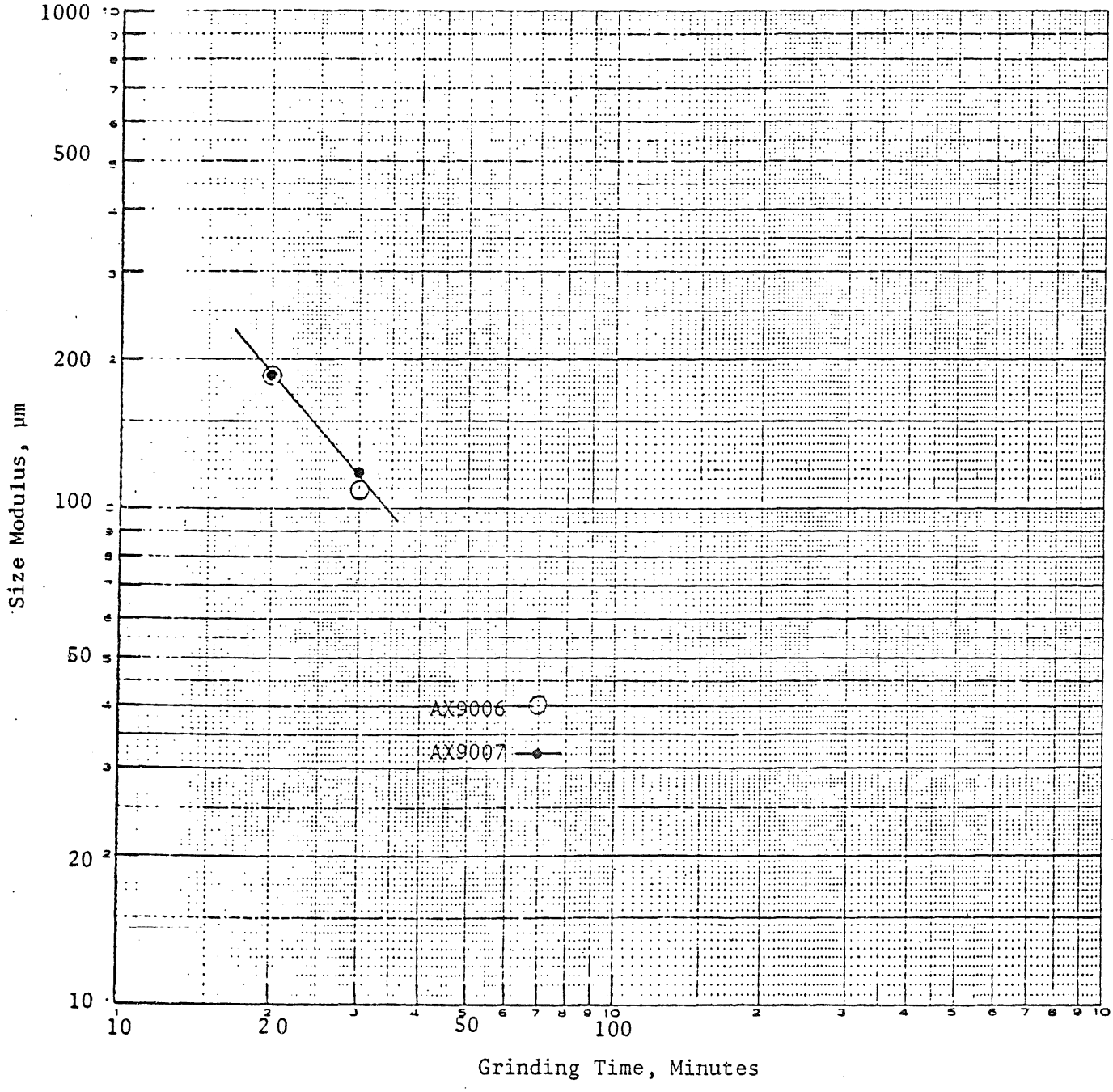


FIGURE 2. SIZE MODULI OF AX9006 AND AX9007 SAMPLES AS A FUNCTION OF GRINDING TIME

fiber [illegible]les, subsieve sizing and size fractionation, and aging tests on tailing water samples.

In the standardized flotation tests each sample was ground to minus 65 mesh (20 minutes), and the ground pulp was transferred to a 2-liter Denver flotation cell, conditioned first with 0.05 pound of KAX per ton for 2 minutes and then with 0.05 pound of MIBC per ton for one minute. The rougher flotation time was fixed at 5 minutes, and the rougher froth thus collected was cleaned once. The cleaner concentrate was reground to minus 270 mesh and the reground pulp was transferred back to a Denver cell and was cleaned successively four times. The cleaner flotation time both before and after regrinding was fixed at 5 minutes. The results of the standardized flotation tests on AX9006 and AX9007 are given in Tables 4(a) and 4(b), respectively, Test 1. The size distributions of their flotation feed and products are given in Tables 5 and 6.

It is to be noted in Tables 4(a) and 4(b) that the copper, nickel, and sulfur analysis data of the rougher tailings were approximately the same for both samples at 0.07 to 0.08 percent, 0.02 to 0.03 percent, and 0.1 to 0.2 percent, respectively. Such observations are in contrast with the results of the other semi-massive sample, AX9004, in which iron sulfides were not fully recovered in flotation and the R Tails analyzed very high in sulfur. The grades of the fourth cleaner concentrates after regrinding (Regr Cl 4 Conc) exceeded 26 percent copper. By compositing the data it can be seen that even the cleaner concentrate prior to regrinding exceeded 13 percent copper, although the siliceous gangue and oxides, estimated as the balance from the sum of the copper, nickel, cobalt, iron and sulfur contents, amounted to 32 and 48 percent, repsectively, for AX9006 and AX9007.

TABLE 4(a). STANDARDIZED AND MODIFIED FLOTATION TEST RESULTS ON AX9006

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Graphite C
Test No. 1 Standardized Flotation Test							
Grind: Rougher -65 mesh							
Regr Cleaner -270 mesh							
Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton							
Flotation Time: Rougher 10 min, Cleaner 5 min							
Rougher pH: 7.3							
Regr Cl 4 Conc	10.59	26.18	0.78	0.054	32.90	30.60	1.89
Regr Cl 4 Tail	2.53	22.97	1.60	0.122	32.80	29.01	
Regr Cl 3 Tail	2.78	19.98	2.33	0.177	31.02	26.43	
Regr Cl 2 Tail	7.29	13.30	2.16	0.158	27.18	19.65	
Regr Cl 1 Tail	10.54	6.92	1.16	0.099	21.17	10.62	
Cl Tail	7.98	0.37	0.105	0.025	10.33	0.66	
R Tail	58.29	0.079	0.033	0.017	10.01	0.17	
Test No. 2 Modified Flotation Test							
Grind: Rougher -65 mesh							
Regr Cleaner -270 mesh							
Reagents: Rougher - KAX 0.2 lb/ton, MIBC 0.05 lb/ton; Scavenger 1 - KAX 0.1 lb/ton; Scavenger 2 - KAX 0.05 lb/ton							
Flotation Time: Rougher - 10 min; Scavenger 1 - 5 min; Scavenger 2 - 3 min; Cleaner - 5 min							
Regr Cl 4 Conc	24.34	23.02	1.86	0.132	32.40	29.10	1.70
Regr Cl 4 Tail	1.39	1.55	0.94	0.085	14.13	3.64	
Regr Cl 3 Tail	2.45	1.11	0.68	0.067	13.27	2.77	
Regr Cl 2 Tail	5.49	0.87	0.55	0.058	12.97	2.04	
Regr Cl 1 Tail	8.86	0.53	0.34	0.042	12.37	1.43	
Cl Tail	12.83	0.185	0.065	0.022	8.97	0.35	
Sc 2 Conc	6.02	0.118	0.042	0.019	10.48	0.26	
Sc 2 Tail	38.62	0.049	0.029	0.018	10.44	0.10	

TABLE 4(b). STANDARDIZED AND MODIFIED FLOTATION TEST RESULTS ON AX9007

Product	% Wt	% Cu	% Ni	% Co	% Fe	% S	% Grahite C
Test No. 1 Standardized Flotation Test Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: KAX 0.05 lb/ton, MIBC 0.05 lb/ton Flotation Time: Rougher 10 min, Cleaner 5 min Rougher pH: 7.7							
Regr Cl 4 Conc	10.95	26.15	1.20	0.098	26.69	30.88	1.45
Regr Cl 4 Tail	0.52	4.00	1.54	0.120	16.13	10.27	
Regr Cl 3 Tail	0.97	2.51	0.94	0.085	11.45	7.19	
Regr Cl 2 Tail	3.20	1.83	0.90	0.083	10.81	6.50	
Regr Cl 1 Tail	6.65	0.74	0.34	0.047	9.60	3.95	
Cl Tail	10.61	0.345	0.061	0.021	9.84	0.76	
R Tail	67.10	0.072	0.023	0.019	8.15	0.11	
Test No. 2 Modified Flotation Test Grind: Rougher -65 mesh Regr Cleaner -270 mesh Reagents: Rougher - KAX 0.2 lb/ton, MIBC 0.05 lb/ton; Scavenger 1 - KAX 0.01 lb/ton; Scavenger 2 - KAX 0.05 lb/ton Flotation Time: Rougher - 10 min; Scavenger 1 - 5 min; Scavenger 2 - 3 min; Cleaner - 5 min							
Regr Cl 4 Conc	12.69	23.98	1.35	0.100	33.24	30.42	1.19
Regr Cl 4 Tail	0.88	1.45	0.92	0.078	14.68	7.09	
Regr Cl 3 Tail	1.56	0.83	0.60	0.056	12.42	4.83	
Regr Cl 2 Tail	3.18	0.465	0.32	0.039	10.08	3.45	
Regr Cl 1 Tail	6.62	0.225	0.174	0.029	14.68	2.21	
Cl Tail	11.47	0.229	0.051	0.017	9.52	0.54	
Sc 2 Conc	3.58	0.208	0.046	0.015	9.36	0.41	
Sc 2 Tail	60.02	0.058	0.021	0.018	9.27	0.050	

TABLE 4(c). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON AX9006

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 1 Standard Two-stage Grind Flotation																	
Regr Cleaner 4	10.59	26.18	0.78	0.054	32.90	30.60	48.68	16.73	12.00	21.58	43.73	89.41	3.27	0.459	0.055	14.14	4.66
Regr Cleaner 3	13.12	25.53	0.95	0.067	32.85	30.26	58.87	25.00	18.53	26.73	53.58	86.88	2.69	0.425	0.053	13.61	3.96
Regr Cleaner 2	15.90	24.59	1.19	0.086	32.52	29.62	68.71	38.11	28.85	32.06	63.57	84.10	2.12	0.362	0.049	13.03	3.21
Regr Cleaner 1	23.19	21.04	1.49	0.109	30.83	26.48	85.76	69.96	53.06	44.34	82.87	76.81	1.05	0.190	0.038	11.69	1.65
Cleaner	33.73	16.63	1.39	0.106	28.11	21.52	98.59	94.56	74.95	58.79	97.98	66.27	0.12	0.036	0.029	10.04	0.23
Rougher	41.71	13.52	1.14	0.090	24.69	17.53	99.12	96.17	79.16	63.87	98.66	58.29	0.079	0.033	0.017	10.01	0.17
Test No. 2 Modified Two-stage Grind Flotation																	
Regr Cleaner 4	24.34	23.02	1.86	0.132	32.40	29.10	96.54	80.17	60.91	48.11	93.77	75.66	0.264	0.148	0.027	11.25	0.62
Regr Cleaner 3	25.73	21.84	1.81	0.129	31.44	27.71	96.89	82.47	63.19	49.32	94.43	74.27	0.242	0.133	0.026	11.19	0.57
Regr Cleaner 2	28.18	20.05	1.71	0.124	29.88	25.55	97.41	85.48	66.23	51.33	95.36	71.82	0.209	0.114	0.025	11.11	0.49
Regr Cleaner 1	33.67	16.93	1.52	0.113	27.12	21.71	98.27	90.79	72.30	55.66	96.82	66.33	0.151	0.078	0.022	10.96	0.36
Cleaner	42.53	13.52	1.28	0.098	24.05	17.49	99.13	96.10	79.32	62.37	98.54	57.47	0.087	0.038	0.019	10.73	0.19
Rougher + Scav 1	55.36	10.42	1.00	0.081	20.56	13.53	99.48	97.52	84.63	69.38	99.20	44.64	0.058	0.031	0.018	11.25	0.12

TABLE 4(d). CALCULATED GRADE AND RECOVERY IN EACH STAGE OF FLOTATION TESTS ON AX9007

Flotation Stage	Concentrate, Cumulative											Tailing, Cumulative					
	% Wt	% Cu	% Ni	% Co	% Fe	% S	Cu Rec	Ni Rec	Co Rec	Fe Rec	S Rec	% Wt	% Cu	% Ni	% Co	% Fe	% S
Test No. 1 Standard Two-stage Grind Flotation																	
Regr Cleaner 4	10.95	26.15	1.20	0.098	26.69	30.88	92.33	59.01	32.52	29.71	82.04	89.05	0.267	0.102	0.025	8.64	0.83
Regr Cleaner 3	11.47	25.14	1.21	0.099	29.03	29.90	93.01	62.61	34.34	30.44	83.25	88.53	0.245	0.094	0.024	8.60	0.78
Regr Cleaner 2	12.44	23.38	1.19	0.097	27.65	28.14	93.78	66.66	36.77	31.45	84.95	87.56	0.220	0.085	0.024	8.57	0.71
Regr Cleaner 1	15.64	18.97	1.13	0.095	24.23	23.72	95.68	79.72	44.98	34.65	90.05	84.36	0.159	0.053	0.022	8.48	0.49
Cleaner	22.29	13.53	0.90	0.080	19.87	17.81	97.26	90.08	54.40	40.50	96.36	77.71	0.109	0.028	0.019	8.38	0.19
Rougher	32.90	9.28	0.63	0.061	16.63	12.31	98.45	93.23	61.09	50.00	98.30	67.10	0.072	0.023	0.019	8.15	0.11
Test No. 2 Modified Two-stage Grind Flotation																	
Regr Cleaner 4	12.69	23.98	1.35	0.100	33.24	30.42	96.05	74.03	41.37	32.92	88.33	87.31	0.143	0.069	0.021	9.85	0.58
Regr Cleaner 3	13.57	22.52	1.31	0.099	32.06	28.89	96.46	77.49	43.65	33.93	89.70	86.43	0.130	0.060	0.020	9.80	0.52
Regr Cleaner 2	15.13	20.28	1.24	0.095	30.01	26.44	96.87	81.39	46.58	35.41	91.53	84.87	0.117	0.051	0.019	9.76	0.44
Regr Cleaner 1	18.31	16.84	1.08	0.085	26.54	22.45	97.34	85.72	50.49	37.91	94.05	81.69	0.103	0.040	0.018	9.74	0.32
Cleaner	24.93	12.43	0.84	0.070	23.39	17.09	97.81	90.92	56.68	45.48	97.48	75.07	0.092	0.028	0.018	9.31	0.15
Rougher + Scav 1	36.40	8.59	0.59	0.053	19.01	11.87	98.63	93.52	63.20	53.98	98.85	63.60	0.066	0.022	0.018	9.28	0.08

TABLE 5. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF AX9006

Size, mesh	Cl 4 Conc % Wt	Cl Tail % Wt	R Tail % Wt
	Test 1. Standardized Flotation Test		
+65		2.88	4.45
+100		9.94	20.29
+150		8.46	21.73
+200		8.46	20.66
+270	2.98	6.63	9.89
+400	6.42	8.63	6.26
-400	90.60	55.00	16.72
	Test 2. Modified Flotation Test		
+65		4.77	5.98
+100		12.50	22.08
+150		12.23	22.79
+200		12.59	24.04
+270	2.14	8.18	9.01
+400	5.71	13.85	6.47
-400	92.15	35.88	9.63

TABLE 6. WET SCREEN ANALYSIS RESULTS ON FLOTATION PRODUCTS OF AX9007

Size, mesh	Cl 4 Conc % Wt	Cl Tail % Wt	R Tail % Wt
	Test 1. Standardized Flotation Test		
+65		1.88	4.09
+100		9.42	19.18
+150		10.55	25.58
+200		7.69	16.37
+270	4.78	7.16	10.23
+400	9.15	9.04	7.67
-400	86.07	54.26	16.88
	Test 2. Modified Flotation Test		
+65		1.61	3.27
+100		8.19	17.89
+150		10.65	28.46
+200		15.13	16.15
+270	4.23	8.14	11.15
+400	7.57	8.29	8.85
-400	88.20	47.99	14.23

Davis magnetic tube tests were performed on Cl 4 Conc samples to explore the feasibility of a copper-nickel separation, but the magnetic concentrates amounted to only 0.01 and 0.03 percent by weight, respectively, for AX9006 and AX9007. Hence, chemical analyses on the magnetic separation products were not made. The pyrrhotite in the present samples appears to be the nonmagnetic variety. Another point of interest is that cubanite, normally magnetic, was not recovered in the Davis magnetic tube tests. As mentioned previously, the AX9007 sample is cubanite-rich.

With the present samples virtually all the sulfide minerals were recovered in the standardized flotation tests, quite contrary to the results obtained on the other semi-massive sample, AX9004. Nevertheless, the modified flowsheet, developed on AX9004 and illustrated in Figure 3, was tested on the present samples. The metallurgical results of the flotation tests are given in Tables 4(a) and 4(b), and the size distribution data in Tables 5 and 6. As expected from an increased use of the collector, the recoveries of copper, nickel, and sulfur increased, particularly in the cleaner stages. The grades of the concentrates did not suffer as much, analyzing over 20 percent copper beyond the second cleaner following regrinding, see the columns of "Cumulative % Cu." Yet the recoveries of sulfur remained close to or well over 90 percent, which could be interpreted to mean that the pyrrhotite contents in the present samples were low.

The flotation results in the rougher and the scavenger circuits are summarized in Table 7. It is evident in the table that the improvements in the grades of tailings by the scavenger operations were relatively minor.

To explore the possibilities of finding unusual trace elements in the tailings and of concentrating certain trace elements in the concentrates,

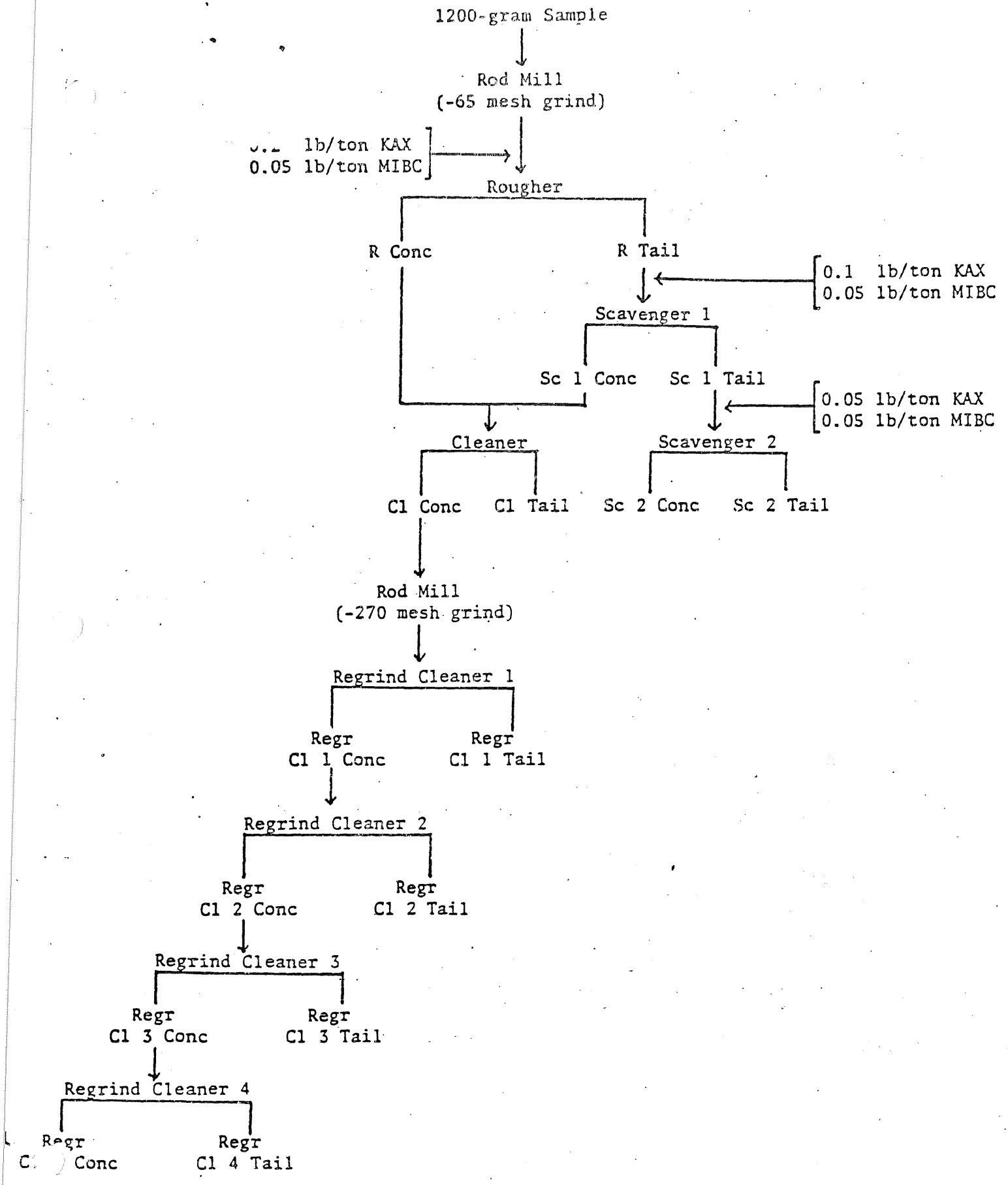


FIGURE 3. MODIFIED FLOTATION FLOWSHEET OF TEST 2 FOR BOTH AX9006 AND AX9007

the flotation feed and product samples were analyzed by Barringer Research Ltd. The results are given in Tables 8 and 9. Some of the elements of concern, such as arsenic, cadmium, and lead, were below the limits of their detection. Of interest is the presence of minor quantities of silver and zinc. It is also noted that the copper, nickel, iron, and cobalt analyses by Barringer and by the MRRC were in reasonably good agreement.

TABLE 7. SUMMARY OF FLOTATION RESULTS IN ROUGHER AND SCAVENGER CIRCUITS

Sample	Test No.	Product	% Wt	% Cu	% Ni	% S
AX9006	1	R Tail	58.29	0.079	0.033	0.17
	2	Sc 1 Tail	44.64	0.058	0.031	0.12
		Sc 2 Tail	38.62	0.049	0.029	0.10
AX9007	1	R Tail	67.10	0.072	0.023	0.11
		Sc 1 Tail	63.60	0.066	0.022	0.070
	2	Sc 2 Tail	60.02	0.058	0.021	0.050

Pulp liquors taken prior to the addition of the flotation reagents and immediately following the rougher flotation step were centrifuged to remove suspended solids for trace element analyses. The results are given in Table 10 and 11. The tailings were filtered, sealed in plastic bags wet, and delivered to the Environmental Engineering Group of the Department of Civil and Mineral Engineering for leaching study.

TABLE 8. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9006 (TEST 1 - STANDARDIZED FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	7.71		0.285		9.64		9.74	
B	nd		nd		nd		nd	
Be	0.00027		nd		0.00034		0.00037	
Ca	0.753		0.0247		1.06		0.958	
Cu	6.03	6.38	26.20	26.18	0.33	0.37	0.071	0.079
Fe	14.40	11.86	25.90	32.90	9.06	10.33	9.11	10.01
Mg	3.24		0.0978		3.62		4.03	
Mn	0.0615		0.00377		0.069		0.0743	
P	nd		nd		nd		nd	
Ba	0.048		0.0029		0.111		0.118	
Se								
Te								
s	nd		nd		nd		nd	
Si								
Sr	0.0158		0.000464		0.0212		0.0199	
Zr	0.00471		0.0004		0.00751		0.00723	
Ti	0.625		0.0211		0.743		0.807	
V	0.0243		0.00281		0.0276		0.0316	
Zn	0.0302		0.0522		0.0229		0.0224	
Th	0.00059		nd		0.00106		0.00081	
K	0.473		nd		0.837		0.669	
Na	0.90		0.10		1.21		1.13	
Cd	nd		nd		nd		nd	
Cr	0.0308		0.00951		0.060		0.0343	
Co	0.0294	0.050	0.0313	0.054	0.0082	0.025	0.0042	0.017
Ag	0.00169		0.00409		0.00082		0.00017	
Mo	nd		0.0021		0.0009		nd	
Ni	0.462	0.505	0.693	0.78	0.0863	0.105	0.0165	0.033
Pb	nd		0.006		nd		nd	

3**

* Conventional AA analyses
**0.0000001% = 1 ppb

TABLE 9. TRACE ELEMENT ANALYSIS RESULTS IN PERCENT OF FLOTATION PRODUCTS ON AX9007 (TEST 1 - STANDARDIZED FLOTATION)

	Feed (-65 mesh)		Concentrate (-270 mesh)		Cleaner Tailing (-65 mesh)		Rougher Tailing (-65 mesh)	
	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*	Barringer	MRRC*
Al	7.04		0.44		8.66		8.08	
B	nd		nd		nd		nd	
Be	0.00022		nd		0.00027		0.00026	
Ca	2.05		0.102		2.45		2.42	
Cu	3.43	3.20	23.80	26.15	0.299	0.345	0.0611	0.072
Fe	13.80	7.42	24.70	26.69	10.70	9.84	10.90	8.15
Mg	3.01		0.151		3.10		3.51	
Mn	0.111		0.00711		0.107		0.129	
P	nd		nd		0.079		0.060	
Ba	0.0547		0.0029		0.0967		0.0867	
Se								
Te								
As	nd		nd		nd		nd	
Si								
Sr	0.0156		0.000876		0.0200		0.0189	
Zr	0.00878		0.00058		0.00852		0.0102	
Ti	1.16		0.0407		1.11		1.31	
V	0.0245		0.00306		0.0247		0.0276	
Zn	0.0237		0.0504		0.0207		0.0227	
Th	0.00077		nd		0.00118		0.00069	
K	0.546		nd		0.844		0.698	
Na	1.26		0.11		1.55		1.48	
Cd	nd		nd		nd		nd	
Cr	0.026		0.0131		0.0497		0.0224	
Co	0.0154	0.027	0.0518	0.098	0.0061	0.021	0.0049	0.019
Ag	0.00085		0.00437		0.00039		0.00020	
Mo	nd		nd		nd		nd	
Ni	0.214	0.228	1.00	1.20	0.048	0.061	0.013	0.023
Pb	nd		0.023		nd		0.011	
Hg**								

* Conventional AA analyses
**0.0000001% = 1 ppb

TABLE 10. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9006 (TEST 1 - MINUS 65 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		0.04	0.26			
B		nd	0.00			
Ba		0.04	0.04			
Be		nd	nd			
Ca		5.21	4.95			
Cu		0.036	0.039			
Fe		0.15	0.194			
K		20.0	nd			
Mg		3.24	2.29			
Mn		0.0682	0.0455			
Na		12	6			
P		0.8	nd			
Se						
Te						
Pb		0.3	nd			
Si		0.742	0.820			
Sr		0.0186	0.0135			
Ti		0.004	0.003			
V		0.008	0.002			
Zn		0.26	0.09			
Th		0.066	nd			
Ag		0.009	nd			
As		nd	nd			
Cd		nd	0.20			
Co		0.09	nd			
Cr		0.017	0.015			
Mo		0.44	nd			
Ni		0.17	0.17			
Zr		0.009	nd			

TABLE 11. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON FEED AND TAILING WATER SAMPLES OF AX9007 (TEST 1 - MINUS 65 MESH GRIND)

	Distilled Water	Feed Water	Tailing Water			
			immed.	1 day old	1 week old	1 month old
Al		0.21	0.30			
B		2.00	2.00			
Ba		nd	nd			
Be		nd	nd			
Ca		6.10	3.90			
Cu		0.022	0.032			
Fe		0.047	0.259			
K		nd	nd			
Mg		3.32	1.99			
Mn		0.0227	0.0455			
Na		9	5			
P		nd	nd			
Se						
Te						
Pb		nd	nd			
Si		1.39	1.48			
Sr		0.0135	0.0084			
Ti		nd	0.005			
V		nd	nd			
Zn		0.06	0.09			
Th		nd	nd			
Ag		nd	nd			
As		nd	nd			
Cd		nd	nd			
Co		nd	nd			
Cr		0.017	0.010			
Mo		nd	nd			
Ni		0.11	nd			
Zr		nd	nd			

4.0 SUMMARY

Eleven different samples of copper-nickel bearing Duluth gabbro were individually tested in bench scale for their concentratabilities by flotation using two standardized procedures. During the tests a number of parameters of environmental concern were determined. One of the standardized flotation procedures was a metallurgically simple flowsheet involving grinding to minus 200 mesh followed by flotation (referred to as 'One-stage Grind Flotation' in this report). The second was a more complex flowsheet involving coarse grinding to minus 65 mesh followed first by flotation and then by regrinding of the flotation concentrate to minus 270 mesh and reflotation (referred to as 'Two-stage Grind Flotation'). The latter flowsheet is expected to require less energy and to lower the dust generation potential in tailings ponds. The following summarizes the observations made on the eleven individual samples.

4.1 GRINDING CHARACTERISTICS

Size distributions of mineral particles produced by crushing and grinding can frequently be represented by the Schuhmann equation

$$y = 100\left(\frac{x}{k}\right)^m \qquad \ldots (1)$$

where y = weight percent finer than size x, x = size in μm, k = size modulus (a constant) for a given size distribution, and m = distribution modulus (a constant). A log-log plot of Eq. 1 yields a straight line of slope m, which intersects the 100 percent ordinate line at a size equal to k. The distribution modulus, m, can vary in the range of about 0.5 to

1 depending on the material and on the type and size of grinding mills. The smaller the value of m, the more abundant are the fine particles for a given mesh-of-grind. The size distribution plot deviates from linearity at coarse sizes, generally above 80 percent.

The Duluth gabbro samples ground in a laboratory rod mill were shown to follow the Schuhmann equation with a distribution modulus, m, of 0.90±0.08. Log-log plots of the size moduli, k, against corresponding times of grind showed linear relationships with minimal spread, which indicated the similarities of these samples in their grinding characteristics. Only limited success was achieved, however, in attempting to quantify the grindabilities of these samples from the above data.

The linearity of the Schuhmann plots, not only for ground products but also for flotation tailings, would permit us to estimate the percentages of the minus 5-μm fraction by extrapolating, which could be related to the dust generation potential from dried tailings ponds. Table 1 summarizes the minus 5-μm contents of the rougher tailings in both one-stage and two-stage grind flotation tests together with the distribution moduli. The minus 5-μm fractions in the rougher tailings (R Tail) averaged 4.7 percent at a 200-mesh grind and 2.4 percent at a 65-mesh grind. In this group of bench-scale test data there appeared to be no particular correlation between m and the minus 5-μm fraction. On a pilot plant sample of a scavenger tailing, however, m was determined to be 0.6, and the minus 5-μm fraction was estimated by extrapolation to be 14 percent at a nominal 65-mesh grind.

TABLE 1. GRINDING CHARACTERISTICS OF DULUTH GABBRO SAMPLES IN LABORATORY ROD MILL AND DUST GENERATION POTENTIAL FROM FLOTATION TAILINGS

Sample	m	Fraction % -5 μm in R Tail	
		-200 mesh grind	-65 mesh grind
IP9002	0.92	4	2.5
IP9003	0.89	3	1.5
DP9002	0.94	4	2
US9001	0.82	5	2.5
AX9001	0.97	4	3
AX9002	0.89	5	3
AX9003	0.91	6.5	2.5
AX9004	0.70	6	3
AX9005	0.97	4.5	1.5
AX9006	0.94	-	-
AX9007	0.94	-	-
Average	0.90	4.7	2.4
Standard Deviation	±0.08	±1.1	±0.6

4.2 GRINDING ENERGY REQUIREMENTS

The power required to grind a material from a given feed size to a given products size can be estimated by using the following equation:[9]

$$W = Wi\left[\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right] \quad \ldots\ldots (2)$$

where W = power consumption expressed in Kwh/short ton, Wi = Bond work index, P = size in μm of screen opening through which 80 percent of the product will pass, and F = size in μm of the screen opening through which 80 percent of the feed will pass. The value determined by Eq. 2 applies to wet, closed circuit grinding in an 8-foot diameter inside liners ball mill.

The Bond work index (Wi) of Duluth gabbro increases as the mesh-of-grind becomes finer. The data available at the Mineral Resources Research Center are plotted on a log-log scale in Figure 1. Ball mill work indices from 80 percent passing 65 mesh to 325 mesh data on several different Duluth gabbro samples can be represented by a straight line. To estimate the Bond work indices for nominal 65-mesh and 200-mesh grind samples the laboratory data of the 80 percent passing sizes were averaged. At the 65-mesh grind the average was 156±17 μm and at the 200-mesh grind 61±10 μm. The corresponding Bond work indices would then be 13.5 and 19.5 Kwh per ton, respectively. Using Eq. 2 the grinding energy requirements from 80 percent passing 1/2 inch to these product sizes can be estimated as shown in Table 2.

It is interesting to note that the energy required for a 200-mesh grind is well over twice as great as that for a 65-mesh grind on the laboratory ground samples.

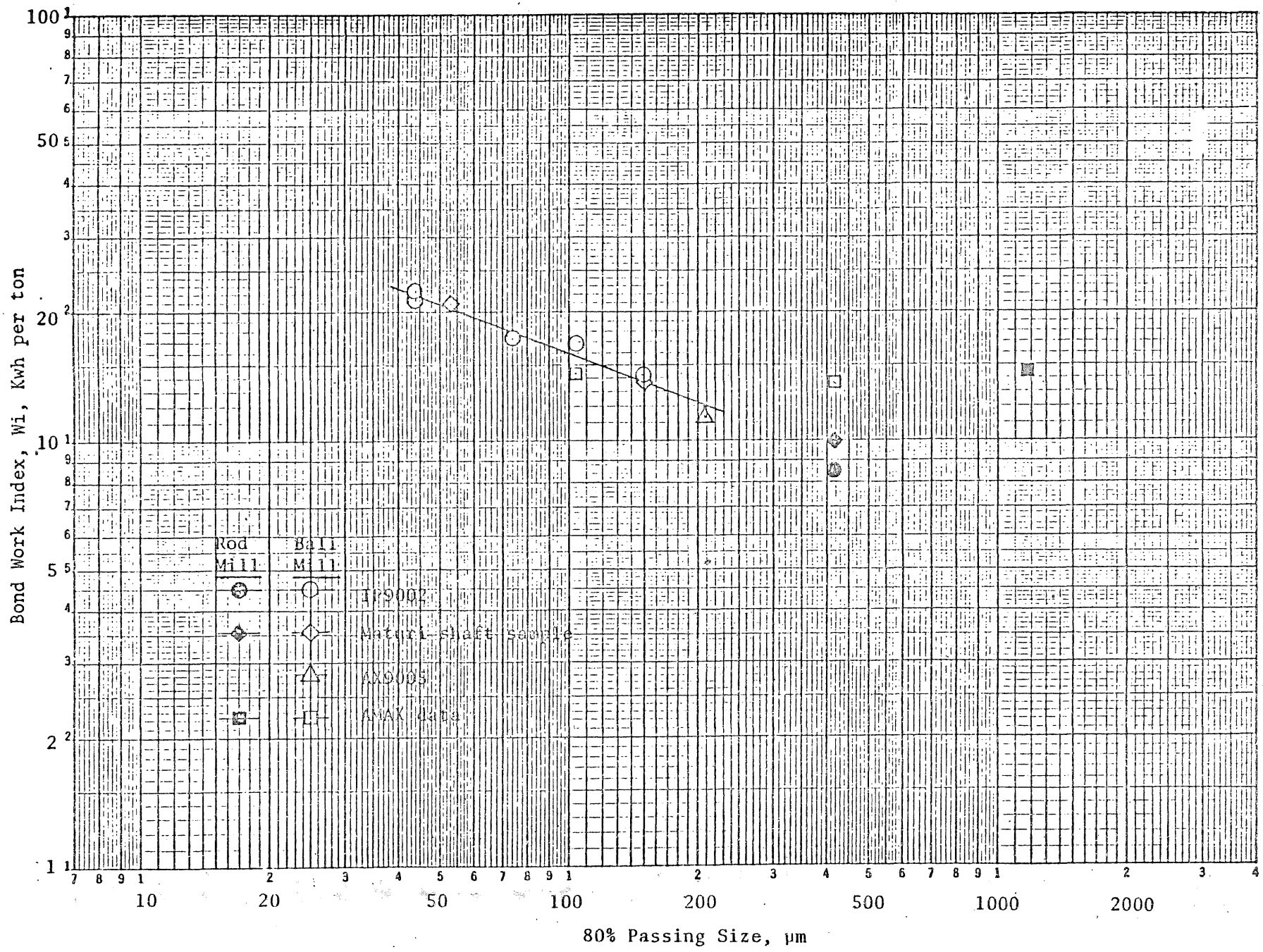


FIGURE 1. WORK INDEX OF DULUTH GABBRO SAMPLES AS A FUNCTION OF MESH-OF-GRIND

TABLE 2. ENERGY REQUIREMENTS OF GRINDING DULUTH GABBRO FROM 80 PERCENT PASSING ONE-HALF INCH TO PRODUCT SIZE

	-65 mesh grind	-200 mesh grind
Feed, 80% passing, μm	12,700	12,700
Product, 80% passing, μm	156	61
Bond Work Index (Wi)	13.5	19.5
Grinding Energy (Kwh/t)	9.6	23.2

To compare the above data with a pilot-plant operation, the size distributions of pilot-plant ball mill feed and ground samples are plotted in Figure 2. In the figure two more lines were drawn to indicate the average size distributions of laboratory ground samples. These lines were drawn to go through the 80 percent passing sizes of 61 and 156 μm with a slope, m, of 0.90 for minus 200 and 65 mesh grind samples. The slope of the line for the pilot-plant ground sample was appreciably less. The value of m was determined to be 0.6 and the 80 percent passing size 110 μm. From Figure 1 the Bond work index (Wi) was found to be 15.5 and the required grinding energy from the ball mill feed with an 80 percent passing size of 17,500 μm to the product size was calculated to be 13.6 Kwh per ton.

In our pilot plant the ball mill (36 x 42 inches) was drawing 8.3 Kwh at a feed rate of 1000 pounds per hour. The power draw of the empty mill was 2.1 Kwh. Therefore, a net power at shell would be 6.2 Kwh. Since the Bond work indices refer to the power required at the mill pinion shaft, a friction loss factor of 2.5 percent, including mill bearings and gear pinion losses[10] must be applied to the above value in calculating the operating

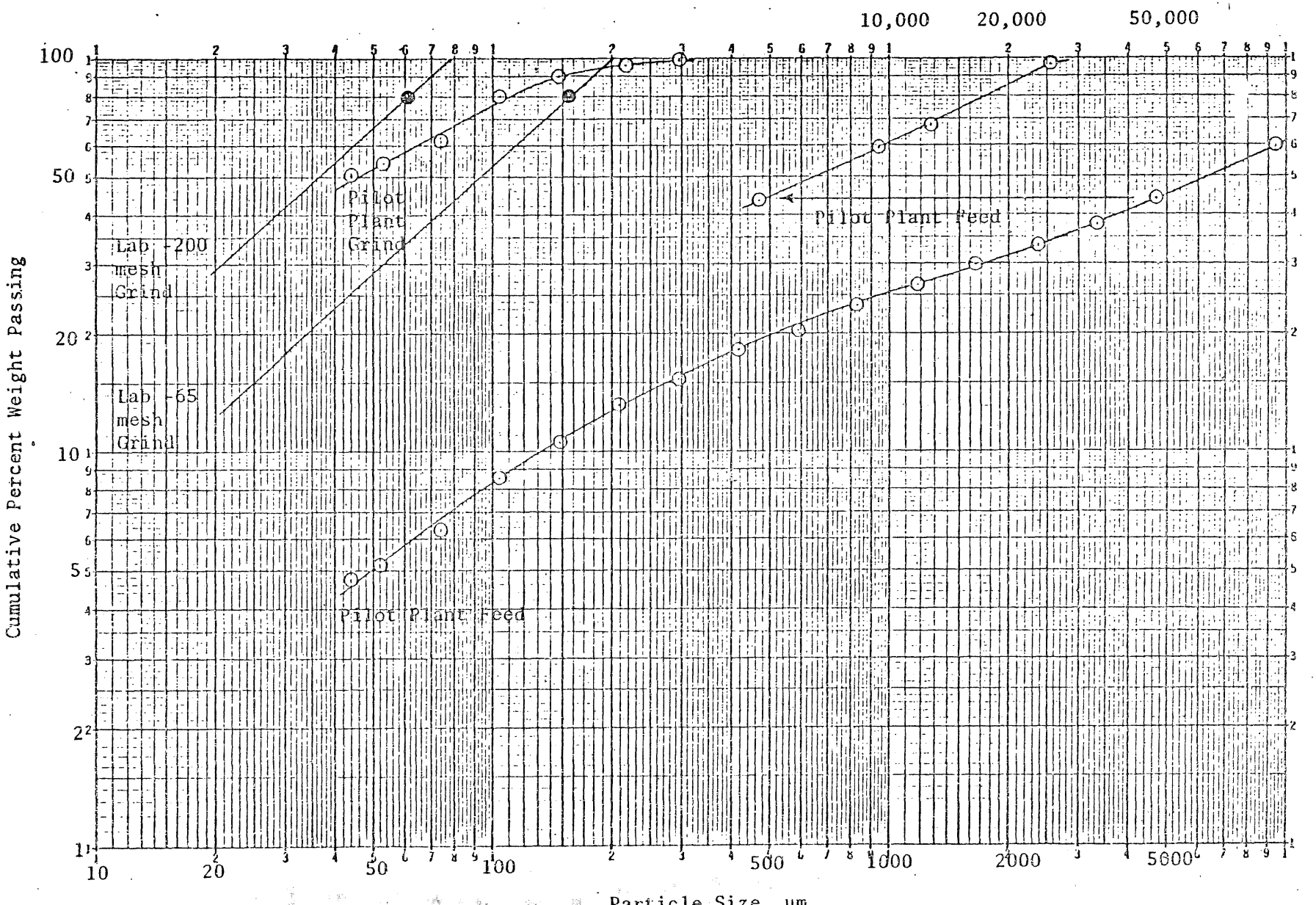


FIGURE 2. SIZE DISTRIBUTION OF LABORATORY GROUND SAMPLES AND PILOT PLANT FEED AND GROUND SAMPLES

work index by the following equation

$$Wio = \frac{W}{\left[\frac{10}{\sqrt{P}} - \frac{10}{\sqrt{F}}\right]} \quad \ldots . \quad (3)$$

where Wio is an operating work index. To compare the work index from pilot plant test results with the Bond grindability test results, two additional efficiency factors are applied, namely, the diameter efficiency factor and the oversize feed factor.[11] The multipliers for the efficiency factors were calculated by using the following equations.

$$\text{Diameter efficiency factor} = \left(\frac{8}{D}\right)^{0.2} = 1.23 \quad \ldots . \quad (4)$$

$$\text{Oversize feed factor} = \frac{Rr + [Wi - 7]\left[\frac{F - Fo}{Fo}\right]}{Rr} = 1.20 \quad \ldots . \quad (5)$$

where D = Mill diameter inside liners in feet = 2.83'

Rr = Reduction ratio = F/P = 159

Fo = Optimum feed size = $4000\sqrt{13}/Wi$ = 3663

Then the operating work index can be caluclated by using Eq. 3 as follows

$$Wio = \frac{6.2 \times 1.025/0.5}{\frac{10}{\sqrt{110}} - \frac{10}{\sqrt{17,500}}} \times \frac{1.20}{1.23} = 14.1 \text{ Kwh/ton} \quad \ldots . \quad (6)$$

The above value of the operating work index is in reasonably good agreement with the Bond work index value of 15.5 Kwh per ton obtained from Figure 1.

4.3 FLOTATION CHARACTERISTICS

In the early stages of the present investigation it became apparent that the copper contents of the rougher tailings approached 0.05 percent irrespective of the samples when they were ground to minus 65 to 100 mesh

and finer, whereas the nickel contents remained virtually independent of the mesh-of-grind. Hence the flotation results as a function of the mesh-of-grind and also of the standardized flotation tests of the eleven different samples were averaged (see Table 3).

TABLE 3. COPPER AND NICKEL CONTENTS IN ROUGHER TAILINGS OF ELEVEN DULUTH GABBRO SAMPLES AT DIFFERENT MESH-OF-GRINDS

Nominal Mesh-of-Grind	Number of Data	% Copper		% Nickel	
		Average	Standard Deviation	Average	Standard Deviation
-48	9	0.085	±0.049	0.054	±0.013
-65	27	0.061	±0.014	0.047	±0.014
-100	10	0.047	±0.011	0.047	±0.015
-200	18	0.045	±0.018	0.049	±0.012

The average values in the table confirm the above observations on the effect of the mesh-of-grind. Based on these observations, the two types of the standardized flotation test schemes, namely, a minus 200-mesh grind (one-stage grind flotation) and a minus 65-mesh grind (two-stage grind flotation), were developed in the present investigation.

In Tables 4(a) and 4(b) the Cl 4 Conc and the R or Sc Tail data on all the Duluth gabbro samples are listed. Excluding the high-sulfide sample (DP9002) and the semi-massive samples (AX9004, AX9006 and AX9007), the weights of the concentrates ranged from 2.1 to 3.4 percent in open circuit (or a ratio-of-concentration of 30-to-1 to 50-to-1) and their copper contents varied from 10.6 to 22.6. The manner in which the concentrate grades vary with the number of cleaning stages may be illustrated by grade-recovery curves for copper as shown in Figures 3(a) and (b). All the curves except

TABLE 4(a). SUMMARY OF CLEANER 4 CONCENTRATE DATA

Sample		% Wt	% Cu	% Ni	% Co	% Fe	% S	Graphite C	Gangue [2]	Recovery, Percent Cu	Ni	Co
One-stage Grind Flotation												
IP9002		2.55	16.71	2.56	0.09	27.92	22.48	0.43	30.24	88.53	55.71	10.55
IP9003		3.13	17.50	3.40	0.12	33.62	26.30	0.19	19.06	78.66	50.02	19.45
DP9002		8.60	8.94	2.32	0.18	44.38	31.71	0.13	12.47	94.75	81.80	55.36
	[1]	10.46	6.89	1.59	0.19	46.80	29.96	0.036	14.57	95.80	78.67	57.51
US9001		3.32	10.62	1.94	0.128	39.94	28.73	0.109	18.64	89.02	55.81	29.86
AX9001		2.08	13.20	1.88	0.088	26.50	19.18	2.85	39.15	85.87	53.79	12.08
AX9002		3.68	15.56	2.75	0.074	27.70	21.48	0.48	32.44	89.75	62.70	25.86
AX9003		3.93	14.00	2.54	0.12	28.18	23.11	2.80	32.05	89.72	52.41	25.00
AX9004		16.13	8.40	3.08	0.25	48.05	33.76	0.96	6.46	93.94	85.71	73.81
	[1]	27.04	4.80	2.18	0.18	56.02	34.80	-	2.02	96.00	91.58	77.78
AX9005		3.39	17.60	2.52	0.161	34.42	28.86	0.62	16.44	90.34	52.26	25.35
Two-stage Grind Flotation												
IP9002		2.48	16.60	3.20	0.166	29.52	25.53	0.48	24.98	85.01	56.92	22.78
IP9003		2.32	19.96	3.56	0.164	34.92	30.73	0.19	10.67	75.55	40.41	15.85
DP9002		3.50	19.98	3.21	0.26	38.81	34.26	0.076	3.48	87.27	55.57	33.71
	[1]	6.93	9.96	2.14	0.23	47.60	35.01	0.038	5.06	89.63	76.21	49.11
US9001		2.06	15.01	2.56	0.162	46.06	34.17	0.084	2.04	77.57	52.65	15.48
AX9001		1.50	17.58	2.78	0.13	29.59	24.95	5.00	24.97	74.94	46.44	14.70
AX9002		2.48	22.62	3.30	0.13	33.26	30.53	0.55	10.16	82.74	57.69	26.38
AX9003		2.80	18.61	2.58	0.14	30.60	27.87	3.61	20.20	84.07	43.28	21.79
AX9004		12.89	9.66	3.40	0.27	47.33	36.35	1.19	2.99	91.62	83.24	72.50
	[1]	15.58	8.02	3.30	0.26	50.81	35.64	-	1.97	95.85	89.47	73.24
AX9005		2.99	19.99	3.36	0.174	25.88	29.30	0.70	21.30	82.74	57.69	26.38
AX9006		10.59	26.18	0.78	0.054	32.90	30.60	1.89	9.49	48.68	16.73	12.00
	[1]	24.34	23.02	1.86	0.132	32.40	29.10	1.70	13.49	96.54	80.17	60.91
AX9007		10.95	26.15	1.20	0.098	29.69	30.88	1.45	11.98	92.33	59.01	32.52
	[1]	12.69	23.98	1.35	0.100	33.24	30.42	1.19	10.91	96.05	74.03	41.37

[1] Modified Flotation Flowsheet
[2] % Gangue = 100 - (% Cu + % Ni + % Co + % Fe + % S)

TABLE 4(b). SUMMARY OF ROUGHER OR SCAVENGER TAILING DATA

Sample	% Wt	% Cu	% Ni	% Co	% S	Cu Loss	Ni Loss	Co Loss
			One-stage Grind Flotation					
IP9002	80.45	0.044	0.05	0.02	0.09	7.36	34.30	61.10
IP9003	81.08	0.068	0.068	0.015	0.10	7.91	25.91	71.71
DP9002	83.01	0.023	0.027	0.012	0.44	2.36	9.19	45.19
	[1] 63.59	0.020	0.027	0.016	0.050	1.68	8.23	50.10
	[2] 56.93	0.019	0.027	0.016	0.028	1.44	7.28	49.11
US9001	84.43	0.03	0.04	0.010	0.032	6.39	29.28	75.59
AX9001	80.47	0.034	0.028	0.013	0.041	8.57	30.95	72.06
AX9002	75.59	0.051	0.048	0.008	0.061	6.05	22.50	63.58
AX9003	79.09	0.039	0.065	0.013	0.093	5.04	27.00	60.89
AX9004	52.46	0.070	0.031	0.013	2.40	2.55	2.81	14.17
	[1] 44.14	0.066	0.033	0.012	0.31	2.15	2.24	13.38
	[2] 38.56	0.068	0.029	0.012	0.14	1.93	1.74	12.66
AX9005	75.56	0.037	0.053	0.015	0.19	4.24	24.54	61.42
			Two-stage Grind Flotation					
IP9002	84.75	0.045	0.044	0.013	0.10	7.87	26.73	73.85
IP9003	90.38	0.055	0.078	0.019	0.21	8.11	34.49	62.44
DP9002	81.07	0.053	0.034	0.015	0.50	5.37	13.64	35.71
	[1] 76.13	0.073	0.027	0.016	0.14	7.18	10.74	58.67
	[2] 72.08	0.069	0.026	0.016	0.09	6.45	9.61	57.51
US9001	89.50	0.075	0.035	0.018	0.10	16.83	31.27	58.34
AX9001	89.04	0.065	0.032	0.011	0.08	6.45	31.74	70.47
AX9002	84.85	0.074	0.045	0.013	0.09	9.22	23.50	58.43
AX9003	83.68	0.07	0.07	0.013	0.18	9.46	35.13	54.78
AX9004	67.55	0.080	0.041	0.010	2.87	3.97	5.28	12.45
	[1] 53.07	0.038	0.020	0.014	0.64	1.55	1.81	9.52
	[2] 50.14	0.035	0.018	0.014	0.24	1.35	1.57	7.93
AX9005	86.05	0.089	0.050	0.014	0.25	10.60	27.15	52.06
AX9006	58.29	0.079	0.033	0.017	0.17	0.88	3.83	20.84
	[1] 44.64	0.058	0.031	0.018	0.12	0.52	2.48	15.37
	[2] 38.62	0.049	0.029	0.018	0.10	00.35	1.95	13.28
AX9007	67.10	0.072	0.023	0.019	0.11	1.55	6.77	38.91
	63.60	0.066	0.022	0.018	0.70	1.37	6.48	36.80
	[2] 60.02	0.058	0.021	0.018	0.05	1.12	5.62	35.17

[1]Sc 1 Tail
[2]Sc 2 Tail

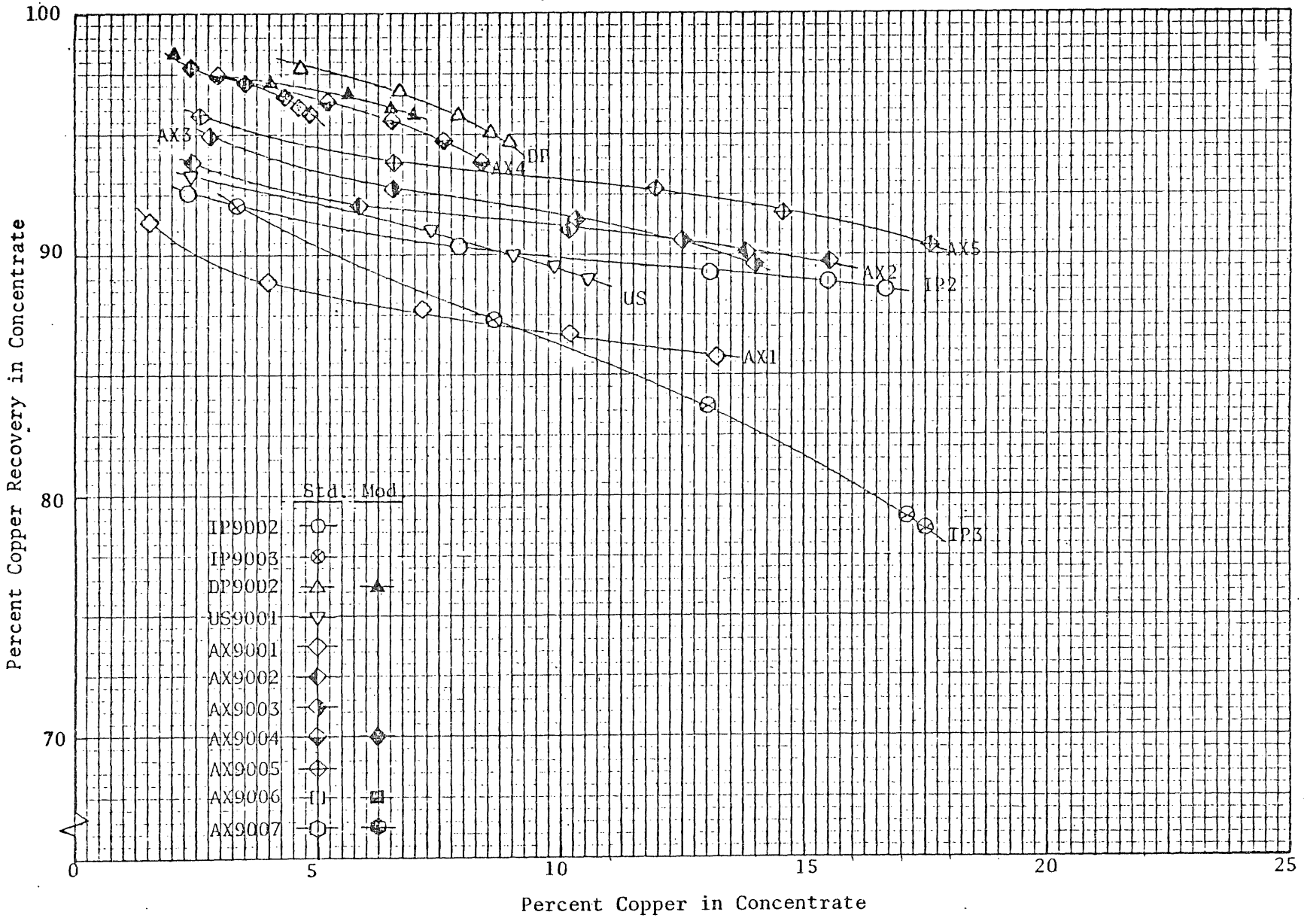


FIGURE 3(a). GRADE AND RECOVERY OF C ER IN ONE-STAGE GRIND FLOTATION

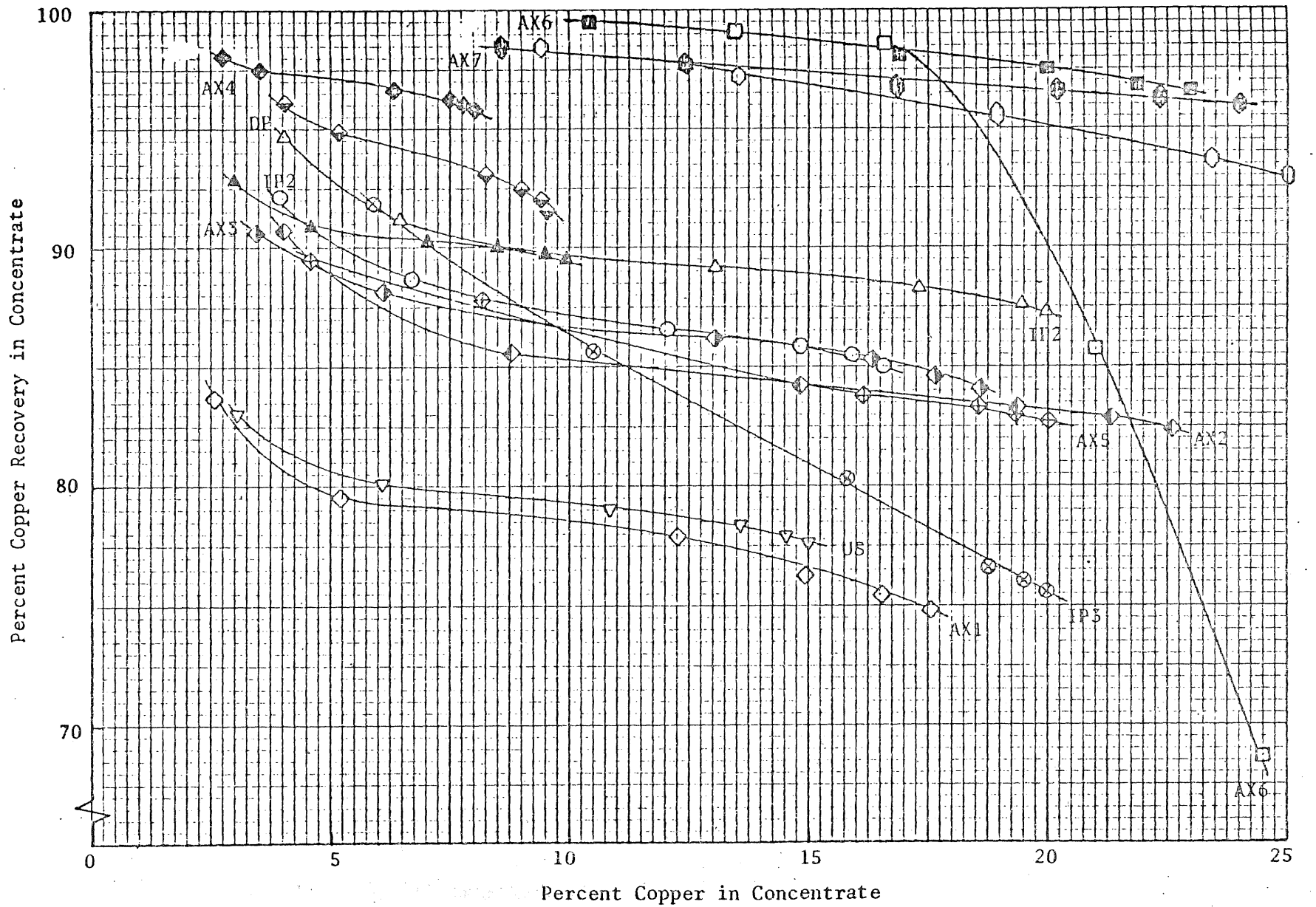


FIGURE 3 (b). GRADE AND RECOVERY OF COPPER IN TWO-STAGE GRIND FLOTATION

DP9002 and the semi-massive samples showed a similar trend, namely, each curve stayed on a plateau of copper recovery over a fairly wide range of grade in copper, and the curves were displaced vertically, more or less, in proportion to their head grades. Such an observation appears reasonable, since the tailing grades were, more or less, constant at 0.05 percent copper. The copper recoveries of the two-stage grind flotation were a few percent lower than those of the one-stage grind flotation for corresponding samples. This observation is in good agreement with the effect of the mesh-of-grind on copper and nickel contents in R Tails (Table 3). Only Sample IP9003 tended to deviate from the other disseminated samples. The copper recovery dropped steadily as the concentrate grade improved, and the grade-recovery curves were virtually superimposable for both minus 65-mesh and minus 200-mesh grind samples.

The weight recoveries and the concentrate as well as tailing grades (Cu, Ni, Co, Fe and S) at any given copper analysis of the concentrates may be estimated by referring to the tables titled, "Calculated Grade and Recovery in Each Stage of Standardized (or Modified) Flotation Tests," on individual samples presented in Chapter 3. It is advisable to computerize these data for facilitating the retrieval of information at any copper analysis specified for a concentrate.

4.4 CHEMICAL AND MINERALOGICAL CHARACTERISTICS OF FLOTATION PRODUCTS

With Samples DP9002 and AX9004 the concentrates could not be upgraded readily to above 10 percent copper due to the presence of large amounts of pyrrhotite. It appears, therefore, that differential flotation should be

considered for these samples in order to reject the pyrrhotite and upgrade the concentrate to, say, 14 percent copper. Only with Sample US9001 could magnetic separation be used to upgrade a concentrate from 11.3 percent copper to 14.3 percent copper.

Pyrrhotite and cubanite are commonly known to be strongly magnetic. Davis magnetic tube tests were performed on Cl 4 Conc samples originally to explore the feasibility of a pyrrhotite separation and also of a copper-nickel separation, perhaps in lieu of differential flotation. The test results are summarized in Table 5. Only Samples US9001 and DP9002 responded to such a treatment scheme producing magnetic concentrates with low copper and nickel contents. Since the other samples contain pyrrhotite and cubanite, it appears that in most Duluth gabbro samples these minerals are of the non-magnetic variety. It is well known that, whereas monoclinic pyrrhotite is magnetic, hexagonal pyrrhotite is not. It is interesting to note also that nonmagnetic cubanite is not commonly mentioned in the literature.

TABLE 5. DAVIS MAGNETIC TUBE TEST RESULTS ON CONCENTRATES (CL 4 CONC)

Sample	% Magnetics
IP9002	1.59
IP9003	0.89
DP9002	5.22
US9001	26.61
AX9001	2.94
AX9002	1.58
AX9003	1.64
AX9004	0.03
AX9005	0.69
AX9006	0.01
AX9007	0.03

Of particular interest in Table 4 are the recoveries of copper, nickel, or cobalt, or especially their losses to R Tails. Excluding the high-sulfide (DP9002) and the semi-massive (AX9004, AX9006 and AX9007) samples, the losses of copper, nickel, and cobalt amounted to, respectively, 4.2 to 16.8 percent, 22.5 to 35.1 percent, and 52.1 to 75.6 percent. The loss of copper was attributable largely to insufficient liberation in the coarse fractions, to extremely fine included chalcopyrite,[10] and to high copper contents in minus 10-μm fractions due presumably to the inefficiency of fine particle flotation. The loss of nickel was appreciably higher. Most of the nickel lost in the tailings was present as unliberated sulfides, and not as fine sulfide particles, nor as nickel in the olivine structure. The amount of olivine in the tailings was in the range of 10 to 18 percent, and the nickel content of the olivine was only about 0.05 to 0.08 percent. The amount of nickel tied up in the olivine structure, therefore, accounts for only 10 to 20 percent of nickel lost in tailings. The loss of cobalt was surprisingly high, but apparently its loss as fine sulfide particles cannot account for the high percentages. Since the unrecovered sulfides would be subject to oxidation in tailing ponds with possible release of heavy-metal ions, further research is needed to identify the forms in which these elements are present and to develop a process to improve their recoveries.

Inductively coupled plasma-atonic emission spectroscopic (ICP) analyses were made on flotation feed and product samples to explore the possibilities of concentrating certain trace elements in the concentrates and of finding unusual trace elements in the tailings. The concentrations of such trace elements as silver, zinc, lead, and mercury in the cleaner concentrates

increased appreciably from their respective feed samples. These increases were thought to be due to the close association of these elements with sulfide minerals. The silver content of Cl 4 Conc ranged from 0.41 to 1.66 ounces per ton, and the zinc content increased from 0.01-0.02 percent in the feed to 0.1-0.2 percent in the Cl 4 Conc. Mercury was analyzed on only three samples, namely IP9002, DP9002 and US9001, and it increased from 60-90 ppb in the feed to 160-200 ppb in the Cl 4 Conc. The cadmium and lead contents in the feed were below the detection limits, but then were upgraded to a level well above their detection limits in some samples of the Cl 4 Conc. It was also noted that, although these elements were reported to be 'not detected,' they often exceeded the detection limit in the smaller size fractions, say minus 10 μm, of the Cl 4 Conc. The detection limits for cadmium and lead were calculated to be 0.0007 percent and 0.0016 percent, respectively, from the information given in Chapter 2, Table 5. Only in one sample (IP9002) arsenic was present in the amount of 0.01 percent and virtually all of it reported in the flotation tailings. The arsenic content of all the other samples was below the detection limit (0.0014 percent).

Detailed mineralogical studies were made on the flotation products from Samples AX9002, AX9004 and AX9005 and similar data are available on Samples IP9002[7] and IP9003.[6] All the data indicated that the copper sulfides (chalcopyrite-cubanite) were essentially liberated from the iron-nickel sulfides (pyrrhotite-pentlandite) at about 400 mesh, indicating that the differential flotation of copper from nickel would be possible. It was also noted that the gangue minerals were well liberated at a 65-mesh grind. This would indicate that flotation tailings could be utilized in by-product recoveries of such mineral commodities as ilmenite, feldspar, olivine, mica,

and graphite, as well as in the separation of hydrous minerals, without further regrinding.

4.5 PRECIOUS METALS

Duluth gabbro contains traces of gold, silver, and the platinum group metals amounting, according to some estimates, to as high as 10 percent of the gross value of the copper and nickel. Only a limited amount of the analytical data is available in the literature on the precious metals in bulk sulfide concentrates on Inco pit samples and none on any crude samples. Table 6 summarizes the results of precious metals analyses on flotation concentrates of the Inco pit sample reported by different laboratories. It is interesting to note that all the results are in good agreement although they were for different bulk flotation concentrates.

The precious metals analyses of several selected concentrates are given in Table 7.

TABLE 6. PRECIOUS METALS ANALYSES OF FLOTATION CONCENTRATES FROM INCO PIT SAMPLES

Source	Analytical Method	Percent		Ounces per ton			
		Cu	Ni	Au	Ag	Pt	Pd
USBM[8]	Spectrographic	10.0	2.2	0.04	1.1	0.036	0.120
		14.4	3.1	0.04	1.5	0.030	0.128
		12.2	2.5	0.04	1.4	0.021	0.122
Inco[12]		13.3	3.6	0.025	0.86	0.035	0.10
MRRC[7]	Spectrographic	27.9	0.33	0.10	1.3	0.03	0.13
		1.0	11.7	0.05	1.2	0.03	0.10
This Report*	ICP	16.7	2.6	-	1.01 0.81	-	-
		16.6	3.2	-		-	-
Thingvold**	NAA	16.7	2.6	0.020	0.71	-	-

* Section 3.1
**Letter dated July 13, 1977

TABLE 7. PRECIOUS METALS ANALYSES OF FLOTATION CONCENTRATES FROM VARIOUS DULUTH GABBRO SAMPLES

Sample	Test No.	Percent		Ounces per ton				
		Cu	Ni	Au	Ag	Pt	P	Pd
IP9003	6 & 7*	18.91	3.85					
AX9004	14**	8.28	3.20					
AX9005	7	19.99	3.36					
	Pilot Plant***	15.02	2.59					
AX9006	2	23.02	1.86					
AX9007	2	23.98	1.35					

* C1 4 Conc from two tests mixed
**Duplicate test sample
***February 23, 1978, 5-7 p.m.

Analytical results on crude and tailing samples were reported in the neutron activation analysis and the Barringer ICP analysis results, although the former method was restricted to gold and silver, and the later to only silver. The neutron activation fails to give platinum and palladium analyses because of interference from scandium. Nevertheless, the amounts of gold and silver recovered by flotation were estimated from the available data and summarized in Table 8. It appears that the recovery of gold was moderately high (in the range of 59 to 75 percent), whereas the recovery of silver was surprisingly low (in the range of 15 to 31 percent). A study on how precious metals are distributed becomes of interest.

4.6 WATER CHEMISTRY OF FLOTATION PULPS

The pulp pH after conditioning and the residual concentrations of potassium amyl xanthate (KAX) and methyl isobutyl carbinol (MIBC) in pulp solutions immediately after flotation are summarized in Table 9. Although the pulp pH averaged 8.8, the freshly acquired samples appeared to give a value in the range of 9 to 9.5. Three samples with low pH values are thought to have been oxidized through long periods of storage or stockpiling (IP9003, DP9002 and US9001). Sample AX9004 probably had a low pH because of a high pyrrhotite content.

The residual concentration of KAX in the pulp solutions ranged from 1 to 1.5 ppm. At a constant level of KAX addition of 0.05 pound per ton, its concentration without adsorption is estimated to be 11.5 ppm, assuming that the purity of the collector used was 69 percent (see Section 2.3.3). A residual concentration of 1 to 1.5 ppm would then correspond to 90 percent

TABLE 8. PRECIOUS METALS RECOVERIES IN BULK SULFIDE FLOTATION OF IP9002 AND AX9002

Test No.	Analytical Method	Product	% Wt	Ounces per ton Au	Ounces per ton Ag	% Dist Au	% Dist Ag
			IP9002				
40. One-stage Grind Flotation	NAA	Cl 4 Conc	2.55	0.020	0.71	59	20
		R Tail	80.45	0.00036	0.10	33	(89)
		Feed	100.00	0.00087	0.090		
	ICP	Cl 4 Conc	2.55	-	1.01 0.81	-	15
		R Tail	80.45	-	0.10	-	53
		Feed	100.00	-	0.15	-	
41. Two-stage Grind Flotation	ICP	Regr Cl 4 Conc	2.48	-	1.30	-	21
		Cl Tail	8.86	-	0.16	-	9
		R Tail	84.75	-	0.10	-	57
		Feed	100.00	-	0.15	-	
			AX9002				
20. One-stage Grind Flotation	NAA	Cl 4 Conc	3.68	0.032	1.15	75	31
		R Tail	75.59	0.00027	0.055	13	31
		Feed	100.00	0.0016	0.134		
21. Two-stage Grind Flotation	ICP	Regr Cl 4 Conc	2.48	-	1.66	-	26
		Cl Tail	8.51	-	0.12	-	6
		R Tail	84.85	-	0.20	-	(106)
		Feed	100.00	-	0.16		

TABLE 9. PULP pH AND RESIDUAL CONCENTRATIONS OF FLOTATION REAGENTS IMMEDIATELY AFTER FLOTATION TESTS

	One-stage Grind Flotation			Two-stage Grind Flotation		
Sample	Pulp pH	KAX (ppm)	MIBC (ppm)	Pulp pH	KAX (ppm)	MIBC (ppm)
IP9002	9.3	1.20	3.00	9.2	1.62	2.91
IP9003	8.3	0.35	6.84	8.0	0.43	10.00
DP9002	8.7	0.74	5.99	8.3	0.76	6.73
US9001	7.8	0.29	6.52	7.4	0.32	6.37
AX9001	9.4	1.99	11.18	9.4	1.97	9.19
AX9002	9.3	1.18	15.05	9.2	1.46	5.28
AX9003	9.4	2.10	8.40	9.3	2.00	10.73
AX9004	8.5	2.08*	5.69	8.5	3.58*	7.91
AX9005	9.1	0.84	3.29	8.8	1.16	2.30
Average	8.87	1.20	7.33	8.67	1.48	6.82
Standard Deviation	±0.57	±0.72	±3.81	±0.69	±1.00	±2.97

*Sc 1 Tail in modified flowsheet

abstraction. The term "abstraction' denoted that the consumption of the collec .. included not only adsorption by minerals, but also precipitation by heavy-metal ions in solution and decomposition. It was noted in pilot-plant runs that the residual KAX concentrations had to be at least 1 to 2 ppm to insure full recoveries of sulfide minerals. The residual KAX in tailing pulps decomposed in a week into a spectrophotometrically inactive form. The exact path of the decomposition of xanthate has not been established, but it is presumed to decompose eventually into H_2O, CO_2 and $SO_4^=$.

The residual concentration of MIBC in pulp solutions centered around 7 ppm. The concentration of MIBC without adsorption is estimated to be 16.7 ppm at 0.05 pound per ton. Since the residual concentration of 7 ppm included the removal in the froth and the dilution water during flotation, a dilution factor similar to that developed for fiber analyses (see Section 2.4.8) should be applied. It appeared that there was very little abstraction of the MIBC by the ground ore. The equilibrium concentrations prior to flotation (see Table 5 in Section 3.6) were seen to be in the range of 15 to 20 ppm. The residual MIBC in the tailing pulps decomposed in a week.

The trace-element analyses of the tailing pulp solutions showed very little unusual elements upon aging. The pulp pH showed a tendency to decrease from near 9 during flotation to about 8 after a month. The concentration of copper ions remained near 10 ppb throughout the period. The concentrations of nickel ions were essentially below the limit of detection by the analytical method used (90 ppb). Frequently the concentrations of copper and nickel ions were higher in pulp solutions prior to the collector addition than after the flotation. The decrease in the presence of ore samples may be attributed to the precipitation of insoluble metal xanthates upon addition of the collector

and to the exchange reactions with iron and zinc sulfides. All the available Barringer data on R Tails averaged 0.013±0.004 percent zinc, and the zinc ion concentrations were seen to increase in many samples to a few tenths of one ppm in a month. In some of the pulp solutions arsenic was reported to be present in the range of 0.2 to 0.4 ppm. Since these values are barely above the limit of detection (0.14 ppm), the significance of such an observation should be carefully evaluated with further testing. In the pulp solutions of virtually all the samples the presence of chromium in the range of 0.006 to 0.1 ppm, of vanadium in the range of 0.001 to 0.03, and of molybdenum in the range of 0.03 to 1 ppm was noted.

Table 10 shows the results of trace element analyses of concentrate and tailing water samples taken during a pilot plant test on a Duluth gabbro similar to AX9005. Of note are the similarities of the analytical results between bench and pilot plant tests, and of concentrate and tailing water samples. The lowering of the pulp pH through sulfuric addition had an effect of raising the concentrations of various ions.

TABLE 10. TRACE ELEMENT ANALYSIS RESULTS IN PPM ON CONCENTRATE AND TAILING WATER SAMPLES OF ORE 1969, LOT 2 (PILOT PLANT RUN ON JANUARY 11, 1978)

		Natural pH				Acid pH			
		Concentrate Water (pH 8.6) Duplicates		Tailing Water (pH 8.7) Duplicates		Concentrate Water (pH 7.8) Duplicates		Tailing Water (pH 6.9) Duplicates	
	Tap Water								
Al		0.23	0.26	0.25	0.33	0.33	0.32	0.40	0.46
B		nd	nd	nd	nd	nd	nd	nd	nd
Ba		nd	nd	nd	nd	nd	nd	0.06	nd
Be		nd	nd	nd	nd	nd	nd	nd	nd
Ca		71.0	72.2	70.3	70.3	102	101	151	152
Cu		0.009	0.009	nd	0.009	0.037	0.02	0.013	0.013
Fe		0.124	0.189	0.044	0.254	0.345	0.319	0.176	0.224
K		13.8	13.8	17.0	17.0	15.4	15.4	21.2	21.2
Mg		38.0	38.5	37.6	37.3	52.5	51.9	72.6	75.1
Mn		0.0789	0.0789	0.0526	0.105	0.289	0.289	1.49	1.37
Na		52	53	56	56	49	49	56	57
P		nd	nd	nd	nd	nd	nd	nd	nd
Se		nd	nd	nd	nd	nd	nd	nd	nd
Te		nd	nd	nd	nd	nd	nd	nd	nd
Pb		nd	nd	nd	nd	nd	nd	nd	nd
Si		2.09	2.08	2.13	2.38	2.85	2.91	3.79	4.06
Sr		0.251	0.253	0.246	0.246	0.335	0.322	0.486	0.492
Ti		nd	0.006	0.006	0.006	0.006	0.006	0.006	0.006
V		0.023	0.022	0.024	0.024	0.033	0.03	0.049	0.05
Zn		nd	nd	nd	nd	nd	nd	nd	nd
Th		nd	nd	nd	nd	nd	nd	0.016	0.018
Ag		nd	nd	nd	nd	nd	nd	nd	nd
As		nd	nd	nd	nd	nd	nd	nd	0.3
Cd		0.09	0.09	0.09	0.09	nd	0.09	0.08	0.08
Co		nd	nd	nd	nd	nd	nd	nd	nd
Cr		0.025	0.03	0.022	0.023	0.032	0.049	0.035	0.053
Mo		0.16	0.15	0.09	0.16	0.2	0.16	0.1	0.1
Ni		nd	nd	nd	nd	nd	nd	nd	nd
Zr		nd	nd	nd	nd	nd	nd	nd	nd

5.0 REFERENCES

1. I. Iwasaki and S. R. B. Cooke: "Absorption Spectra of Some Sulphydryl Compounds," Trans AIME 208 1267 (1957).

2. A. Granville, N. P. Finkelstein and S. A. Allison: "Review of Reactions in the Flotation System Galena-Xanthate-Oxygen," Trans Inst Mining Met, Sect C 81 1 (1972).

3. S. R. Rao: "Xanthates and Related Compounds," Marcel Dekker, New York (1971).

4. B. Philipp and C. Fichte: "Kinetic Studies on the Decomposition of Xanthate," Faserforsch. Textiltech., Vol. 11, pp 118-124, 172-179 (1960).

5. R. Schuhmann, Jr.: "Laboratory Sizing," Powder Metallurgy (John Wulff, ed.), American Society for Metals, Cleveland, Ohio, p. 186 (1942).

6. A. R. Vifian and I. Iwasai: "Mineralogical and Beneficiation Studies of the Copper-Nickel Bearing Duluth Gabbro," Twenty-ninth Annual Mining Symposium, Center for Continuation Study, University of Minnesota, Minneapolis, Minnesota (1968).

7. I. Iwasaki and A. S. Malicsi: "Separation of Copper-Nickel from Duluth Gabbro by a Differential Flotation-Matte Smelting-Matte Separation Process," Final Report, U. S. Bureau of Mines Grant No. GO144109, November 18, 1976.

8. R. B. Schluter and A. B. Landstron: "Continuous Pilot Plant Testing Confirms Floatability of Duluth Complex Sulphides," Eng Mining J., Vol. 177, No. 4, p. 80 (1976).

9. P. W. Weiblen and G. B. Morey: "Mineralogy, Phase Chemistry, and Geologic Occurrence of Sulfide Ores in the Duluth Complex, Northern Minnesota," Final Report, U. S. Bureau of Mines Grant No. GO244005, November 30, 1975.

10. Private Communication from Mr. D. M. Kjos, Allis-Chalmers, Milwaukee, Wisconsin (1978).

11. C. A. Rowland, Jr. and D. M. Kjos: "Rod and Ball Mills," in Mineral Processing Plant Design (Mular and Bhappu, ed.), SME/AIME (1978).

12. "Description of Operating Concepts Required to Establish Preoperational Monitoring for Inco's Proposed Spruce Road Project," July 1975.