PAPER NO. 630

FLOATATION OF COPPER MINERALS FROM NORTH WAZIRASTAN COPPER ORE AT PILOT SCALE

BY
Muhammad Mansoor Khan
Mazhar Rafique
Ihtasham Ullah Khan

FLOATATION OF COPPER MINERALS FROM NORTH WAZIRISTAN COPPER ORE AT PILOT SCALE

M. Mansoor Khan[1], Mazhar Rafiq and Esteshamullah Khan

ABSTRACT

Flotation process parameters were studied to concentrate the copper content i.e. Chalcopyrite of North Waziristan copper ore at Pilot scale as to obtain a copper concentrate suitable for further metallurgical treatment. The important flotation parameters examined were type and dosage of collector, dosage of depressant, dispersant, and frother and conditioning time for collector. During stepwise optimization of flotation parameters, copper was upgraded from 0.9% to 20% in roughing stage, and to as high as 22% in a single stage cleaning with recoveries of over 83%. A flow sheet depicting different products of flotation, for an industrial concentrator, also has been suggested.

INTRODUCTION

In North Waziristan, at places like Shinkai and Degan, huge deposits of copper are available. The copper content in these is very low. The interred ore reserves are 122.71 million tones having a copper content varying between 0.3865% to as high as 2% (FATA DC 1985); (Wang Zhitian, 1996). The purpose of this paper is to concentrate the North Waziristan (Shinkai area) ore to a level suitable for metallurgical treatment. The western part of Waziristan constitutes a complex igneous consisting of hezerbergite pyroxinites, periodities and dunites generally sepentinized. The intrusives comprise of diorites, quarts-diorites, micro-quartz diorites, granodiorites, dolerites and gabbros. Volcanics include grained porphyritic pillows basalts and andesite with sub-ordinate breccia and minor dacite, rhyodaide tuffs and agglomerates.

To confirm the previous studies (Khan M.M 1994) carried out at the laboratory scale petrographic studies of the ore were carried out. It was concluded that the sulphide mineralization is present in the form of the stock work-internally brecciated. The sulphide minerals are disseminated and are in skeletal form. The ore minerals are mostly cube shaped sporadically distributed throughout the rock but also found in the form of cienlets. Chalcopyrite exists as major mineral while malachite, azurite, tenonite as minor valuable minerals and pyrite, pitchlimonite, bronchanite, graphite, chamosite, nimite and quartz gangue minerals (Rafiq Mazhar 1999).

PILOT PLANT FLOTATION STUDIES

The aim of present research is to economically utilize the 122 million tons of copper ore of the North Waziristan area by carrying out pilot scale flotation studies in order to upgrade its copper content by physical concentration method so as to make it suitable for metallurgical treatment to extract blister copper. Pilot scale testing is extremely important before suggesting an industrial size concentrator for a given ore. Flotation process

[1] Faculty members, Department of Mining Engineering, NWFP, University of Engineering and Technology, Peshawar, Pakistan.

parameters such as collector type and dosage, dispersant, pulp density, etc were investigated.

FLOTATION TEST PROCEDURE AT PILOT SCALE

MINERALS

The copper ore was from the Shinkai area (North Waziristan) and assayed 0.9% Cu, 0.0134% Zn, 0.0126% Pb, 0.0110% Co, 0.0067% Ni, 1.740 ppm Ag, and 0.22 ppm Au. Quartz was the main gangue mineral.

COMMUNITION

For each test run of flotation process approximately 100 kgs of copper ore was reduced in size to 80% passing 4mm. The crushed material was wet ground for 20 min in a closed circuit ballmill classifier at a solid-liquid ratio of 1:2.3 (i.e., 30% solids by weight) to 80% passing 75 μm. The coarse particles were difficult to float so the grind was chosen to be fine i.e. 75 μm (Rafiq Mazhar 1999). The fine size grinding also promotes the self induced flotability of the particles (Senior G.D and Trahar. W.J, 1976).

FLOTATION TESTING

The product of the ball mill was conditioned and subjected to flotation in a bank of 25 and 28 litres flotation cells. All the reagents were added in the conditioning stage except caustic soda (NaOH), which was added during the grinding stage as pH regulator. The conditioned pulp was subjected to two roughing stage flotations and one cleaning stage flotation. The concentrates from the Bulk roughing-I and Bulk Roughing-II were combined and cleaned to obtain the final concentrate. For Bulk Roughing-I the parameters investigated were type and dosage of collector, depressant dosage, sulphidizer dosage, pine oil dosage, dispersant dosage and conditioning time. In any stage of flotation i.e. roughing or cleaning, while studying the effect of variation of any parameter on the grade and recovery of copper, the rest of the parameters were kept constant. (Table 2). Normal tap water was used for conducting all the tests. All the reagents were of technical grade except sodium cyanide (NaCN), caustic soda (NaOH) and sodium sulphide. (NA_2S) which were commercial grade. Chemical analyses were carried out with X-Ray Spectrometer System (Joel, Model JSX-603).

FLOTATION TESTS FOR BULK ROUGHING-I

In the flotation method of concentrating minerals fast floating minerals were recovered in bulk roughing stages in order to obtain maximum recovery of valuable minerals (Wills B.A, 1985). The parameters investigated during this stage were type and dosage of collector, pH value, depressant dosage, sulphidizer dosage, pulp density, and pile oil dosage. Generally higher dosages of reagents are used during this stage of flotation.

DETAILS OF TESTS

Fifteen tests were carried out to evaluate the flotation response using different dosages and type of collector. Five tests were conducted each to investigate the effect of varying pH and depressant dosage on the grade and recovery of copper. The effects of sulphidizer was investigated by using dosage in the range of (10-60 gm/ton). Three tests were conducted to investigate the effect of pine oil (frother) by varying its dosage between 25 and 70 gm/ton. The effect of variation in pulp density was investigated by varying it between 15 and 35%. Similarly few tests were conducted to investigate the effect of conditioning time on the grade and recovery of copper. All the products, including tailings, recovered during flotation test work, were dried and analyzed for copper. From the results grade and recovery curves were drawn.

By following the parameters of best test, a rougher concentrate weighing more than 50kgs, having grade 18 to 20% copper was recovered. The concentrate was then routed to the cleaning stage.

DISCUSSION ON RESULTS

COLLECTOR TYPE AND DOSAGE

The curves in figure 1 (Tests 1-5) show that with an increase in NaPX (Sodium Propyl Xanthate) there is a corresponding increase in the grade/recovery of copper (Ralston J, 1991); (Smart R.St.C, 1991). Beyond the dosage of 200 gms/ton, there is a decrease in grade and a slight decrease in recovery. It maybe due to the non specific adsorption of the collector by the gangue particles (Woods Ronald, 1971); (Ross V.E, 1991). And possible due to the development of collector multilayers on the particles, reducing the proportion of hydrocarbon radicals oriented in to the bulk solution. (Smart R.St. C, 1991); (Fuerstenau M.C. and Palmer B.R., 1976); (Smith R.W. and Akhtar S., 1976). Thus reducing the grade of the concentrate the critical dosage of NaPX observed at this stage was 200 gms/ton.

The curves in Figure 2 (Tests 6-10) show a similar behavior of NaEX (Sodium Ethyl Xanthate) to NaPX. By using NaEX the garde/recovery is almost same upto 150 gms/ton but later the recovery has not improved as in case of NaPX. This may be due to the fact that hydrophobic action of Xanthate collectors decreased with the decrease in molecular weight of the alkyl group (Wills B.A, 1985); (Majima, H and Takeda, M, 1968); (Kelly, G. Errol and Spottiswood David J, 1982). The curves in Figure 3 (Tests 11-15) show the effects of KPX (Potassium Propyl Xanthate) on the grade and recovery of copper. The curves reveal a similar behavior of KPX to that copper in the concentrate. Hence Sodium or Potassium cation in collector has no effect on flotation (Crozier. R.D, 1991).

EFFECT OF VARIATION IN pH

In the earliest tests, that is (Tests 1-20), no depressant was used. Thus the collector used in (Tests 1-20) also floated a considerable amount of FeS_2 (Pyrite).Cyanide are widely

used as depressant for pyrite. Examination of cyanide depression is indicated to be electrochemical in nature (Sutherland K.L and Wark W.I,., 1955); (Fuerstenau. D.W, 1962). The positive effect of sodium cyanide on the grade and recovery of Cu are shown in Figure 5. The figure clearly shows that with an increase in depressant dosage there is an increase in the grade and recovery of copper (Elgillani, D.A and Fuerstenau, M.C 1968); (Agar, G.E, Kipie, W.B and Wells, P.F. 1982), but beyond the lmit of 30 gm/ ton there is decrease in grade and recovery of copper. It is due the deactivation of copper particles in the pulp by sodium cyanide as complex cyanides.

EFFECT OF SULPHIDIZER (Na_2S)

The effect of sulfidizer (Na_2S) dosage was also investigated as shown in the figure 6 (Tests 26-30). Sulphidizers are used to activate oxidized minerals and have recently shown to induce flotation. (Walker G.W., Waters C.P., and Richardson P.E, 1983); (Yoon R.H., 1981); (Walker G.W., Waters C.P., and Richardson P.E., 1984); (Luttrel G.M and Yoon R.H., 1984); (Heyes G.W. and Trahar W.J., 1984). Sodium sulfide activates the oxidized copper minerals by forming a psuedo-sulphide layer on them (Franks , 1975). The curves shown a gradual increase in the grade/recovery of copper with increase in Na_2S dosage. The most effective dosage is 50 gms /ton. Beyond that there is a slight decrease in grade and recovery of copper. This may be attributed to depression action of Na_2S through it's ability to decrease the potential of the flotation pulp beyond critical amount. (Woods R, 1976); (Trahar W.J. 1983).

EFFECT OF PILE OIL (FROTHER)

Frother imparts stability to the mineral froth and helps both in achieving higher grade concentrates and recovery. As can be seen in figure 7. (Test34-37). The recovery of Chalcopyrite is enhanced in the presence of frother (Woods R, 1950); (Buckle. A.N and Woods R., 1985); (Buckley. A.N., Hamilton I.C and Woods R., 1976). Pile oil is widely used as a frother. The best dosage found out is 46 gms/ton.

EFFECT OF PULP DENSITY

Figure 8 (tests 31-11) shows that with an increase in pulp density the recovery/grade shows an upward trend due to hindered settling conditions up to 30% (optimum pulp density) (Wills B.A, 1985). However beyond that grade has markedly decreased due to the entrainment of fine slime particles.

EFFECT OF CONDITIONING TIME

It can be observed from figure 9 (Tests 38-41). The conditioning time varies between 10 minutes to 13 minutes. The grade and recovery markedly decreases beyond 13 minutes conditioning time due to the dissolution of Copper Xanthate ions in the equilibrium system. (Khan A, Khan M.M, and Jadoon K.G, 1984).

Table 2. Pilot Scale Flotation Process Parameters

Test	Pulp Density Weight / Volume	Collector Dosage gms/ton	Frother Dosage gms/ton	Pulp pH	Depressant Dosage gms/ton	Sulphidizer Dosage gms/ton	Dispersent Dosage gms/ton	Reagent Conditioning Time (Min.)	
1-5	30	50~250	75	11	0	0	0	10	Bulk Roughing-I
6-10	30	50~250	75	11	0	0	0	10	
11-15	30	50~250	75	11	0	0	0	10	
16-20	30	200	75	10~12	0	0	0	10	
21-25	30	200	75	11.5	10~30	0	0	10	
26-30	30	200	75	11.5	25	10~60	0	10	
31-33	30	200	25~70	11.5	25	50	0	10	
34-37	15~35	200	46	11.5	25	50	0	10	
38-41	30	200	46	11.5	25	50	0	10~18	
42-46	15	40	40	8~12	0	0	0	10	Bulk Roughing-I
47-50	15~30	40	40	10	0	0	0	10	
51-55	25	0~90	40	10	0	0	0	10	
56-59	25	10~90	40	10	0	0	0	10	
60-63	25	60	0~60	10	0	0	0	10	
64-67	25	60	100	10	0	0	0	7~16	
68-71	20	40	35	10~11.67	0	0	0	8	Cleaning-I
72-76	20	40	35	10	0	0	0~180	8	
77-80	20	10~40	35	9.5	0	0	150	8	
81-83	20	10~30	35	9.5	0	0	150	8	
84-87	10~19	20	35	9.5	0	0	150	8	
88-91	15	20	35	9.5	0	0	150	5~14	

FLOTATION TESTS FOR BULK ROUGHING-II

Since the bulk Roughing-I tailing still contained 30% of the total copper, therefore to enhance the recovery of copper, the Bulk Roughing-I tailings were refloated in the 2nd stage (Bulk Roughing-II). The flotation parameters investigated in Bulk Roughing –II were pH; collector type and dosage; frother dosage; and conditioning time (Table 2).

DETAILS OF TESTS

The effect of pH on grade and recovery of copper was investigated by varying pH value between 8 and 12. Similarly tests were also conducted to investigate the effect of pulp density; collector type and dosage; frother dosage and conditioning time (Table 2).

DISCUSSION ON RESULTS

The curves in figures 10-15 reveal the behavior of parameters investigated in the Bulk Roughing–II. In these tests no activator (Na_2S) and depressant (NaCN) were used. As it was reasonably assumed that most of the oxidized copper minerals have been sufficiently sulphidized due to Na_2S addition in the bulk roughing-I. Similarly a considerable amount of free Iron and pyrite have been depressed in the same stage by the NaCN addition. Any small amount of Iron if still existed in the pulp could be depressed by caustic soda (NaOH) added as pH regulator in this stage. In conducting tests for investigating the effect of pH the pulp density and collector dosage were kept constant (table 2). The better results were obtained at the pH of 10. This decrease in pH value maybe attributed to low dosages of collectors used in these tests as compared to the same type of tests performed in the first cycle of flotation (Work and Cox, 1934). The best pulp density is between 22 and 25%. As can be seen in figure 11. No doubt the range is comparatively lower than that observed in Bulk roughing-I. It confirms as to why it is a normal practice to decrease the pulp density in secondary roughing and cleaning operations of the flotation circuits in mineral processing plants. Although it increases the cost of de-watering the concentrate but it does improve the overall metallurgical output (Wills B.A. 1985). Two types of xanthates were tested in a total of nine tests. The response of NaPX was better than NaEX, which maybe due to the fact that xanthates of higher homologous series are more efficient in the absence of any activator (Wark I.W and Cox, 1937). Of the total number of tests conducted the best results for pine oil (frother) were observed at 46gm/ton. Conditioning time was also varied at an incremental value of 3 from 7 to 16 minutes. Considering the Figure 15 it is clear that the conditioning time of 10 minutes is better both in respect of quality and cost of concentrate.

FLOTATION TESTS FOR CLEANING-I

The concentrates from the Bulk Roughing-I and Bulk Roughing-II were cleaned to get the concentrate of desired grade. In flotation circuit the fast floating material is recovered in the roughing section, while the more reluctant fraction is recovered by scavenging certain losses into the tailings have to be accepted cleaning of the rougher concentrate is usually necessary to reach smelters grade. The parameters investigated during this stage

Flotation Process Parameters Investigated for Bulk Roughing I

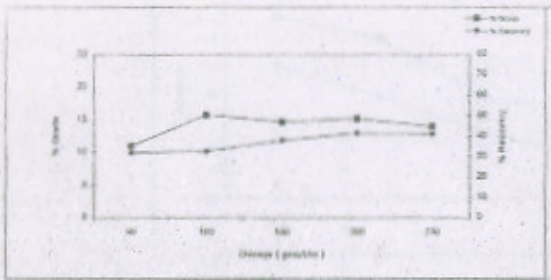


Figure. 1 Effect of Collector (NaPX) on Grade and Recovery of Copper

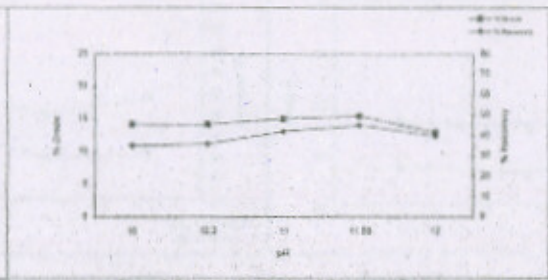


Figure. 4 Effect of pH on Grade and Recovery of Copper

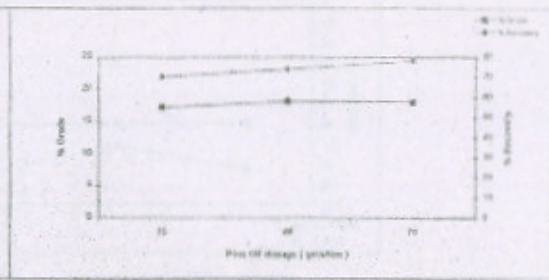


Figure. 7 Effect of Frother (Pine Oil) on Grade and Recovery of Copper

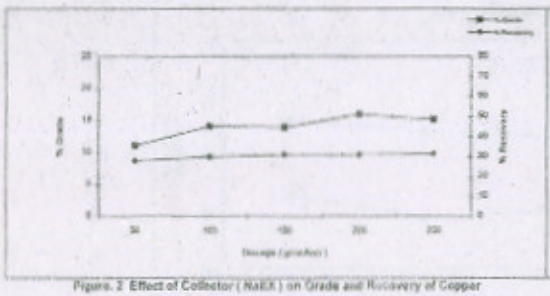


Figure. 2 Effect of Collector (NaEX) on Grade and Recovery of Copper

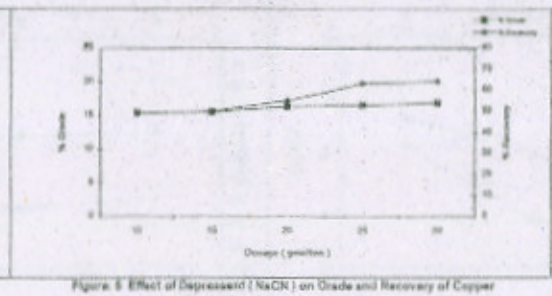


Figure. 5 Effect of Depressant (NaCN) on Grade and Recovery of Copper

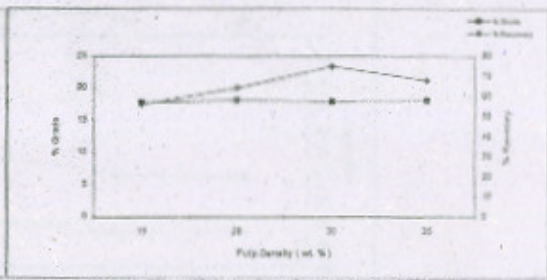


Figure. 8 Effect of Pulp density on Grade and Recovery of Copper

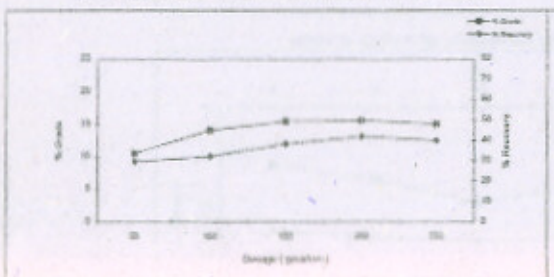


Figure. 3 Effect of Collector (KPX) on Grade and Recovery of Copper

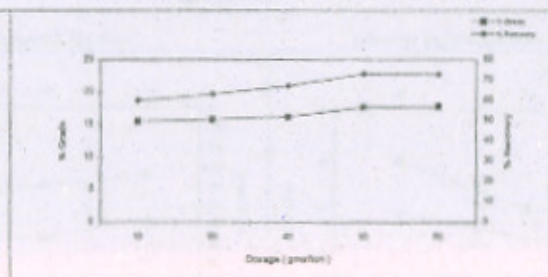


Figure. 6 Effect of Sulphidizer (Na_2S) on Grade and Recovery of Copper

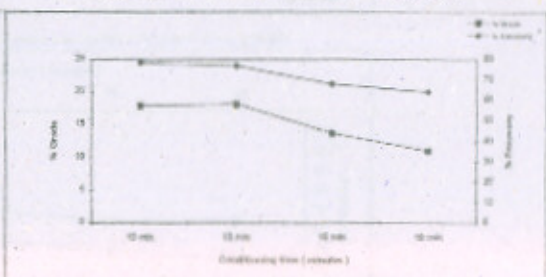


Figure. 9 Effect of Conditioning time of Collector (NaPX) on Grade and Recovery of Copper

Flotation Process Parameters Investigated for Bulk Roughing II

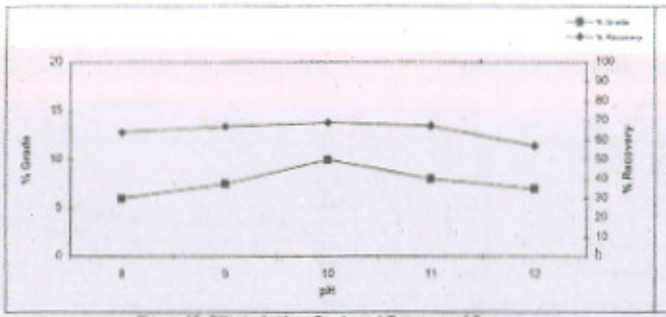


Figure.10 Effect of pH on Grade and Recovery of Copper

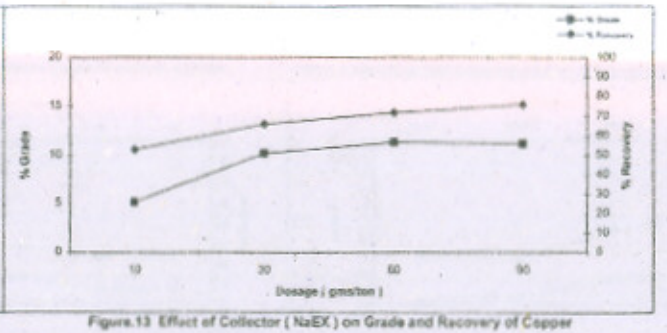


Figure.13 Effect of Collector (NaEX) on Grade and Recovery of Copper

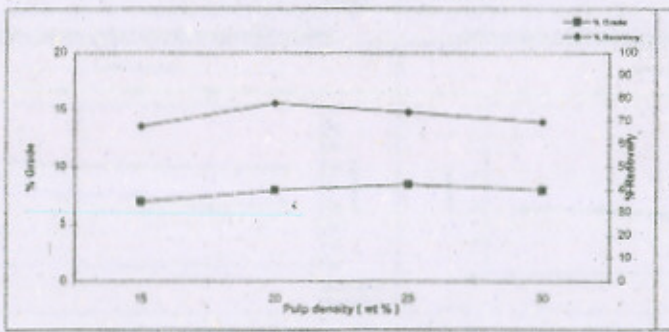


Figure. 11 Effect of Pulp density on Grade and Recovery of Copper

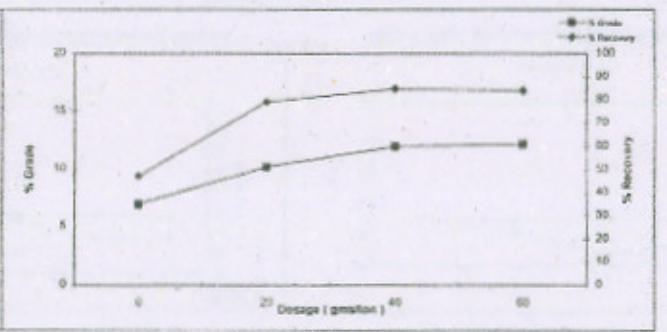


Figure. 14 Effect of Frother (Pine Oil) on Grade and Recovery of Copper

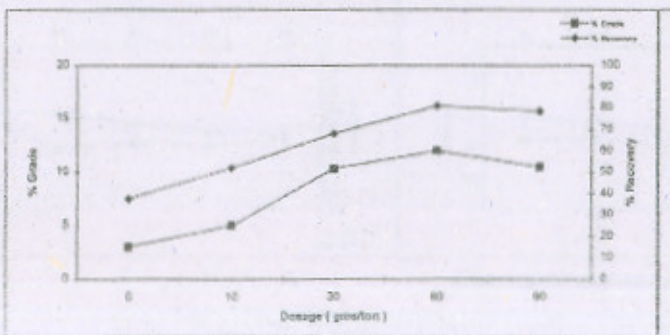


Figure. 12 Effect of Collector (NaPX) Grade and Recovery on Copper

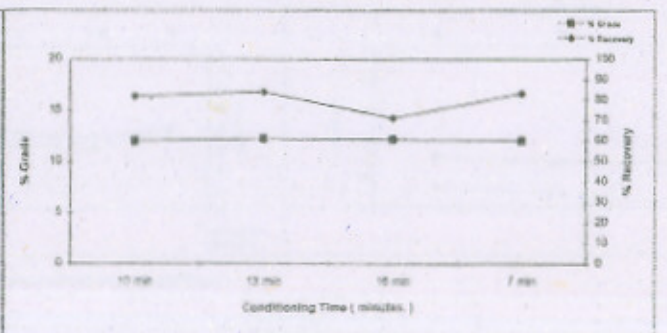


Figure. 15 Effect of Conditioning time on Grade and Recovery of Copper

Flotation Process Parameters Investigated for Cleaning I

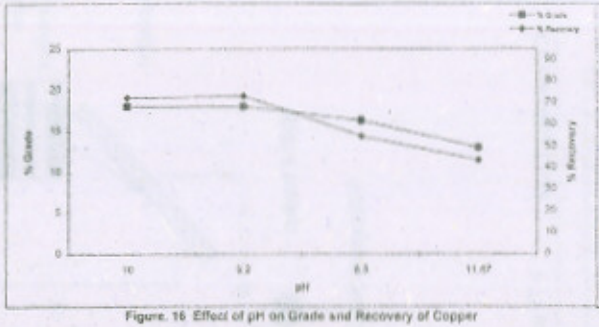


Figure. 16 Effect of pH on Grade and Recovery of Copper

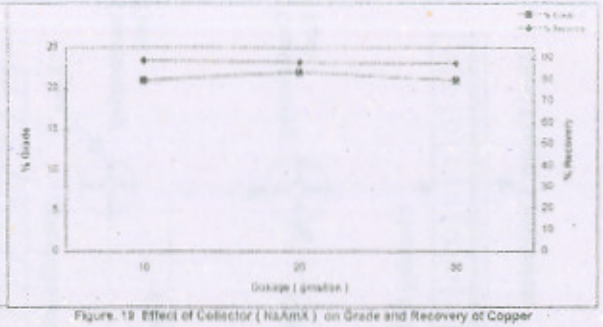


Figure. 19 Effect of Collector (NaAmX) on Grade and Recovery of Copper

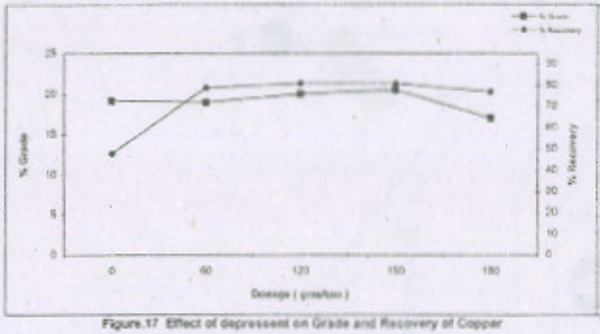


Figure.17 Effect of depressant on Grade and Recovery of Copper

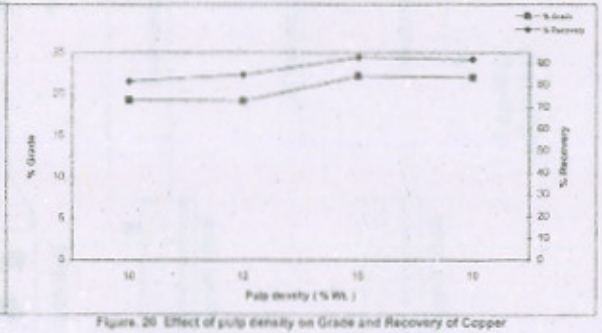


Figure. 20 Effect of pulp density on Grade and Recovery of Copper

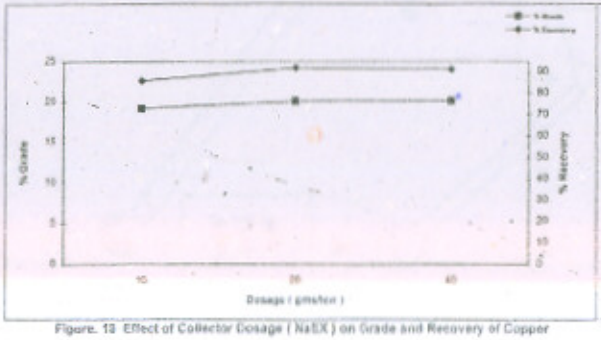


Figure. 18 Effect of Collector Dosage (NaEX) on Grade and Recovery of Copper

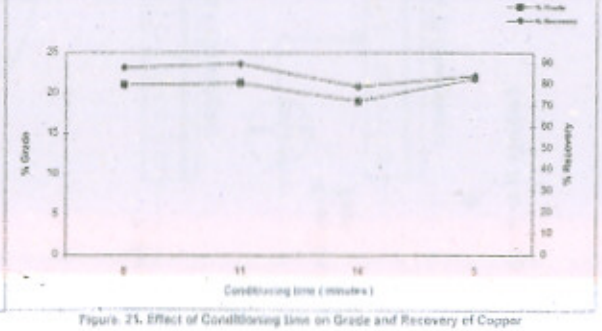


Figure. 21. Effect of Conditioning time on Grade and Recovery of Copper

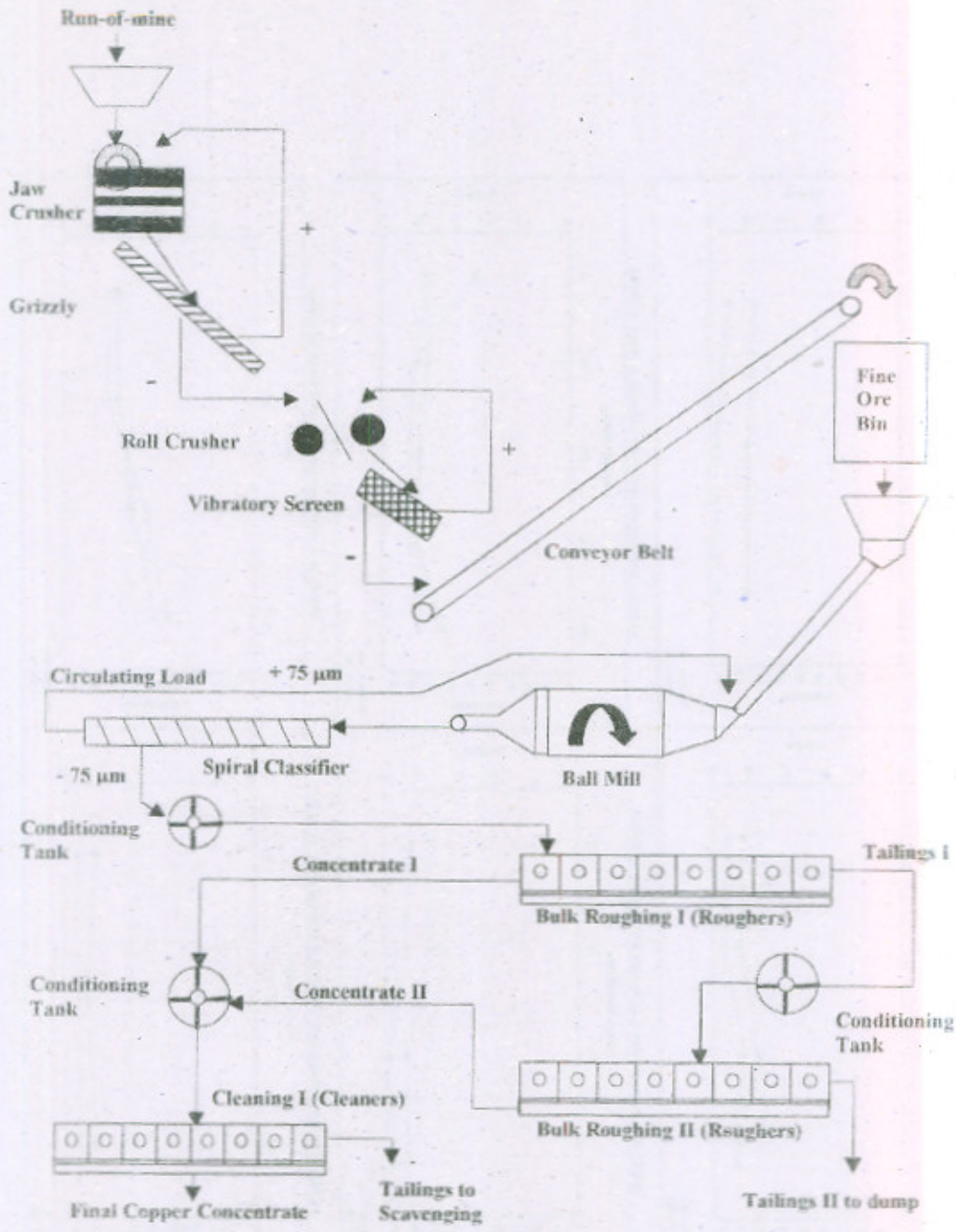


Fig-22 Flowsheet for Copper Concentration at the Mineral Cocentration Pilot Plant

DETAILS OF TESTS

Five parameters were investigated in this cycle of flotation (Figure 16-21). According to the results of the tests the recovery almost improved by almost 40%) as the pH increased from 8.5 to 9.2. This pH value maybe relatively low as compared to Bulk Roughing-I flotation. Cycle due to the decrease in the concentration of collector (Work and Cox, 1934) and lower pulp density (20%) maintained for these tests. Sodium Silicate usage further enhanced the grade and recovery. This maybe due to the dispersive effect of Sodium Silicate on the co-agulated slime particles (Fe-hydroxides precipitates or oxidized sulphide particles) (Smart R. St. C. 1991) formed on copper sulphide mineral particles. The response of NaAmX was better than NaEX, which maybe due to its stronger collecting action on the particles. In the previous tests in this cycle of flotation the pulp density was maintained at 20%. However reducing it to 15% did improve the output of the concentrate in terms of grade and recovery. Cleaner separations are obtained with dilute pulps, in order to increase selectivity (Poling G.W, 1980). The effect of conditioning time was negligible in the range of (5-8 minutes). Hence minimum time of conditioning (5 minutes) was considered suitable. (Figure 21).

SUMMARY AND CONCLUSIONS

The results obtained by pilot scale studies indicate that it is possible to achieve good separation of copper from the gangue material, though the nature of the valuable minerals with gangue has insignificant effect on the selectivity of copper bearing minerals. Taking into account the nature of the ore, the up-gradation achieved is quite satisfactory. The collector dosage needs to be investigated to reduce its consumption especially in the Bulk Roughing-I cycle. Moreover, to further reduce the cost of treatment the effect of lime should be studied in place of caustic soda because of its lower cost. The grade of copper concentrate obtained through single stage cleaning is 22% which can be further enhanced to 28-30% by adding another cleaning stage. Hence for obtaining higher grades and recoveries it is suggested that for a four stage flotation technique should be employed. A proposed flow sheet of copper concentrator prepared by the Department of Mining Engineering after pilot scale studies is presented in Figure 22.

The parameters established as a result of pilot scale studies are summarized in Table 3 & 4.

Table 3. Typical flotation conditions and reagent consumption

Time (in minutes)				Flotation reagents (gms/ton)						
	G.t	C.t	F.t	NaPX	NaOH	NaCN	Na_2S	Na2S	Na_2SiO_3	Pine Oil
Bulk Roughing-I	20	10	12-15	200	-	2200	25	50	-	46
Bulk Roughing-II	-	8	12	60	-	1100	-	-	-	46
Cleaning-I	-	5	12	-	20	800	-	-	150	35

G.t=Grinding time, C.t=conditioning time, F.t=Flotation time.

Table 4. Typical flotation conditions and results for various stages of flotation.

	P.d %	PH	Cu %	Recovery %
Bulk Roughing-I	30	11.58	20-21	70-71
Bulk Roughing-II	25	10	13-13.5	80-83
Cleaning-I	15	10	22-23	91-93
Final Concentrate	81-83% cumulative recovery			

ACKNOWLEDGEMENTS

The authors endorse the co-operation extended to them in conducting research by the hardworking technical staff of Mineral Processing Laboratory and X-Ray Fluorescence Spectrometer Laboratory, NWFP, University of Engineering and Technology, Peshawar.

REFERENCES

Agar G.E, W.B. Kipie, and P.F. Wells, 1982, XIV Mineral Processing Conference, Toronto Canada, Paper IV-1.

Badshah Mian Sayed, 1985, Record of FATA Development Corporation.

Buckley A.N and Woods R., 1985, Proc, Int. Symp. On Electrochemical in Mineral and Metal Processing, Electr. Chem. Soc., p-84,286.

Buckley A.N., Hamilton I.C and Woods R., 1976, K.S.E Forssberg (editor), Flotation of Sulphide Minerals, Volume 6 in Developments in Mineral Processing, Elsevier.

Crozier. R.D, 1991, "Sulphide collector mineral bonding and the Mechanism of flotation" by, Mineral Engineering Vol. 4, Nos 7-11, pp 839-858.

Elgillani D.A and Fuerstnau M.C, 1968, Trans. SME/AIME 241:437.

Fuerstenau M.C and Palmer B.R., 1976, "Anionic flotation of oxides and silicates, " Chap –7. in Flotation, A.M. Gaudin Memorial Volume, M.C. Fuerstenau (Ed.), AIME/SME.

Franks, F. in water- A comprehensive Treatise (F. Franks, Ed.), 1975, Plenum Press, New York, Vol. 4, p-5.

Heyes, G.W and Trahar, W.J. 1984, Proceedings International Symposium on Electrochemistry in Mineral and Metal processing (P.E.Richardson, S.Srinivasan, and R.Woods, eds.), Electrochemical society, Pennington, N.J., 1984, pp. 219-232.

Kelly G.Errol and Spottiswood, David.J., 1982, "Introduction to Mineral Processing", John Wiley and Sons Inc., ISBN (0-471-03379-0, pp.307-313)

Khan, A; Khan M.M and Jadoon, K.G., March, 1984, "Flotation studies on North Waziristan Copper Ore", Proceedings of Seminar on "Prospects and Problems of Mineral based industries in Pakistan", Peshawar, Published by the Department of Mineral based Industries in Pakistan", Peshawar, Published by the Department of Mining Engineering., NWFP University of Engineering and Technology, Peshawar.

Luttrel. G.M and Yoon, R.H. 1984, Int. J. Min. Proc. 13:271.

Majima, H. and Takeda, M., 1968, "Electrochemical studies of the Xanthate Diaxanthogen system on Pyrite", Trans. AIME, 241, pp-431-436.

Mansoor. M. Khan, 1989, Proceedings of the First seminar on problems and prospects on mineral based industries in Pakistan.

Poling G.W, 1980, "Selection and Sizing flotation Machines", Mineral processing Plant design by Mullar and Bhappu, 2nd edition, ISBN 0-89520-269-7, pp 887-906.

Ross. V.E, 1991. "Behavior of particles in flotation froths" Minerals engineering. Vol-4, Nos 7-11, pp. 959-974.

Rafiq. Mazhar, 1999, "Pilot scale studies of North Waziristan Copper Ore", MSc thesis.

Ralston J., 1991, Minerals Engineering, Vol 4, Nos. 7-11, pp859-878.

Senior, G.D. Senior and Trahar, W.J., 1991., "The influence of metal hydroxides and collectors on flotation of chalcopyrite", Int. J. Min process.

Smart R. St. C, 1991, "Surface layer in base metal sulfide flotation" by, Mineral engineering, vol 4, Nos. 7-11, pp 891-909.

Smith R.W and Akhtar S., 1976, "Cationic Flotation of oxides and Silicates," Chapter 5 in flotation, A.M. Gaudin Memorical volume, M.C. Fuerstenau (Ed.). AIME/SME.

Sutherland, K.L and I.W. Wark, 1955, Principle of Flotation, Australian I.M.M.

Fuerstenau D.W (Ed.) 1962, Froth Flotation 50th Anniversary volume, AIME/SME.

Trahar, W.J, 1983, Int. J Min. Proc. 11:57.

Trahar W.J, and Warren L.J, 1977, "the Flotability of very fine particles – A review", Int. J. Miner, Process., p-3, 103-131.

Walker, G.W and Waters, C.P and Richardson. P.E, 1984, Proceedings International Symposium in Electrochemistry in Mineral and Metal processing (P.E.Richardson, S.Srinivasan, and R.Woods, eds), Electrochemical society, Pennington, N.J., pp 202-218.

Walker, G.W., Walker C.P, and Richardson, P.E October 1983, Extended abstracts Vol. 83-2, Electrochemical society, Pennington, N.J., p-766.

Wang Zhitian, 1996, Lecture no Distribution and Metallogenic Models of Large copper deposits of the world and North Waziristan copper ore.

Will. B.A, 1985, Mineral Processing Technology, 3rd edition, Chap 12, pp 378-462.

Woods R. (1950), Chemistry in Australia 57, pp-392.

Woods. R, 1976, Flotation-A.M. Gaudin Memorial Volume, (M.C. Fuerstenau, Ed.). American Institute of Mining Engineers, New York, 1976, Vol. 1, pp 298-333.

Wark, I.W and Cox A.B, 1934, Trans. AIME 112:189.

Wark I.W and Cox A., 1937, "Experimental investigation of the effect of xanthate of the magnitude of contact angle of a bubble on the surface of minerals", New Investigations in the field of flotation theory, (Papers). ONTI.

Yoon. R.H., 1981, Int. J. Min. Proc. 8:31.