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DEVELOPMENT OF INDIGENOUS COLUMN FLOTATION TECHNOLOGY AT NML FOR THE BENEFICIATION OF LOW GRADE ORES

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Abstract: NML Madras Centre has designed and developed indigenous automated flotation columns as part of its long term R&D program on the utilization of low-grade ores of India. Both laboratory size and semi-commercial flotation columns were extensively field tested in different mineral processing plants owned by Hindustan Copper Limited, Hindustan Zinc Limited, Kudremukh Iron Ore Company Limited, Sociedade De Fomento Industrial Limited, Bharat Gold Mines Limited, Gujarat Mineral Development Corporation Limited and Indian Rare Earths Limited for the beneficiation of copper, lead and zinc, iron, gold, fluorspar and sillimanite. State-of-the-art equipment was incorporated in both laboratory and semi-commercial flotation columns. Advantages of column flotation technology over conventional flotation machines and salient features of the NML flotation column were discussed in the present paper. Flotation test results obtained both by flotation column and conventional cells were compared. The paper also highlights the potential of column flotation technology in achieving better metallurgical results compared to conventional flotation cells.

Keywords: copper ore, iron ore, gold ore, column flotation, beneficiation, sulfide ores, oxide ores.

1. INTRODUCTION

The steady depletion of mineral resources and the general policy on mineral conservation have necessitated the effective utilization of low-grade finely disseminated ores. The utilization of such reserves may help to maintain an adequate supply of minerals to meet both economic and strategic needs of our nation. Since the yield of low-grade ores is very low, escalation in in-put costs is inevitable. Further more, fines generated during mining, milling and other metallurgical operations are to be processed not only to recover the values but also on environmental considerations. Presently, large amount of such mineral values are discarded as fines and ultra-fines due to lack of suitable technology to process them. In order to recover values from low-grade ores and from the fines generated during various operations, an efficient technology is essential. The problems associated with processing of fine particles were identified and discussed in detail by earlier investigators[1-3].

Flotation is one of the main unit operations in mineral industry for the separation of valuable minerals from gangue. The process of flotation is mainly affected by the small mass of the particle. Low momentum, slime coating and high reagent consumption are the most frequently discussed difficulties. Models based on interception theories and hydrodynamics highlighted the importance of bubble size for the flotation of fine particles. The probability of particle-bubble collision[4-7] and collection efficiency was found to depend on the ratio of particle to bubble size. As the size of the bubble plays a vital role in flotation process, extensive research was focused on controlling the bubble size. Conventional flotation cell has its own limitations in producing fine bubble

as first developed flotation column during 1967, various aspects of column flotation technology were pursued by Finch and Dobby[9].

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The concept of counter-current contact between the downward flowing slurry with rising air bubbles forms the essential basis of column flotation. The column consists of two zones namely, recovery and cleaning. The conditioned mineral slurry is fed through a side inlet located about one third of the height from the top. The mineral particles while settling down by gravity are encountered with rising air bubbles generated through a sparger fixed at the bottom of the column. The continuous head on collision between the counter current air bubbles and mineral particles ensures the flotation of hydrophobic minerals. When the mineralized bubbles reach the upper portion of the flotation column that is, the cleaning zone, fresh water was sprinkled to minimize the process water entering the froth. While the throughput of the circuit is mainly determined by the cross sectional area of flotation column, the length of the recovery and cleaning zones determine the recovery and grade of froth product respectively. The column is preferred over conventional cells due to the following reasons.

a) In mechanical flotation cells, air bubbles are formed by the swirling action of the impeller that breaks down the stream of incoming air into small bubbles in the presence of frother in pulp. The turbulent hydrodynamic conditions enhance the detachment of mineral particles from the air bubbles. The relative collision velocity between co-current air bubbles and mineral particles is negligible in the mechanical flotation cells thus resulting in a much shorter effective residence time than the nominal one. On the other hand quiescent conditions prevailing in the recovery zone of flotation column provides many opportunities for head on collision.

b) The entrainment of unwanted material in froth product is a serious draw back of conventional machines. Due to high turbulent conditions, fine gangue material could be easily carried into the froth after getting either entrained in the liquid or mechanically entrapped with the particles being floated. Thus the grade of the concentrate is affected in the conventional machines. The absence of turbulence at the slurry-froth interface of the column minimizes the chance of physical entrapment of unwanted gangue particles. As the mineralized froth enters the cleaning zone, the entrapped gangue particles are washed down by wash water mechanism in the column. It was reported that less than 1 % of the process water enters the concentrate product stream during steady state column operation[9]. Consequently the selectivity will be enhanced and in turn high-grade concentrates could be obtained. This inherent cleaning action is the main reason that the flotation column finds its application mostly in cleaning process.

Industrial use of flotation columns has experienced a remarkable growth since the beginning of the 80s. From a single plant application in eastern Canada for Cu-Mo separation, several mineral industries all over the world have implemented column flotation technology for different applications [10-12].

NML Madras Centre is pursuing the development of column flotation technology since 1990. Initially, a laboratory flotation column (75 mm dia) was developed and demonstrated in various mineral-processing industries. After successful campaign of the laboratory size flotation column, semi-commercial size (0.5 m dia) column was developed for online testing and data generation for scale-up studies. The semi-commercial column was successfully installed and commissioned in different mineral processing plants and carried out continuous trials to establish the feasibility of column flotation technology.

2. SALIENT FEATURES OF NML COLUMN

2.1 Column

While laboratory column (74 mm dia) was fabricated out of flanged modules of Plexiglas, steel was used for semi-commercial column. Overall column design permits the variation of parameters such as column height, feed injection point and froth depth.

2.2 Sparger

Internal type spargers were used both in lab size and semi-commercial size flotation columns. In lab size column, sintered bronze disc fixed over a bed of glass beads was used for uniform dispersal of air. Discs of different porosity were used to obtain desired bubble size. The disc can be changed depending on the bubble size and bubble density requirement. Ceramic tubes made of silicon carbide were used in the case of semi-commercial column. Provision was made to insert or take out these spargers without disrupting the continuous column operation.

2.3 Pumps

In order to control the feed flow and tailing discharge, electronically controlled diaphragm metering pumps were used in lab size column. The pumps are capable to deliver an accurately measured volume with an error of +/- 3 %. Capacity of the pump can be adjusted by changing the stroke length manually or automatically from a remote controller. Facility for digital display of pumping capacity was also incorporated in the controller. In the case of semi-commercial size flotation column, conventional slurry pumps were used.

2.4 Level controller

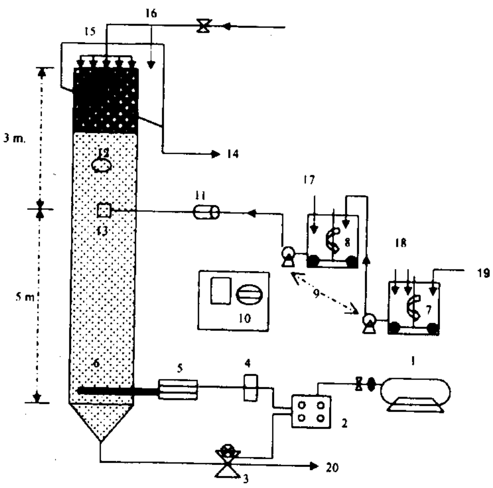
A Differential Pressure Transmitter (DPT) was used to maintain the interface between the slurry and froth. The output signal from DPT was looped to the stroke controller of the tailing discharge pump via microprocessor based controller, so that pumping rate could be changed automatically to maintain the interface level at a fixed froth depth. The interface can be visualized on the LCD screen of the controller. During steady state, the interface level can be maintained at a constant value of ± 10 mm. In the case of semi-commercial column, out-put signal of DPT was fed to an electro-pneumatic control valve.

2.5 Flow measurement

Magnetic flow meter with digital display of flow-rate and totaliser was incorporated to measure and control the wash water flow. However, purge rotameters were used to measure the air flow rate of the sparging.

2.6 Wash water distribution

Wash water distributor was provided for the uniform distribution of water above the froth surface covering the entire cross section of the column. For easy monitoring of the column parameters, all the controls were mounted in a centralized panel. The schematic diagram of semi-commercial column system is shown in Fig.1.



1. Air Compressor
2. Air Distributor Panel
3. Pneumatic Control Valve
4. Air Rotameter
5. Pressure Header
6. Air spargers
7. Conditioner I
8. Conditioner II
9. Pumps
10. Control Panel
11. Mag. Flow Meter
12. Differential Pressure Transmitter
13. Feed Point
14. Froth Discharge
15. Wash Water Distributor
16. Launder Water Distributor
17. Collector addition
18. Frother addition
19. Feed inlet
20. Tailings discharge

Fig. 1. Schematic diagram of semi-commercial flotation column

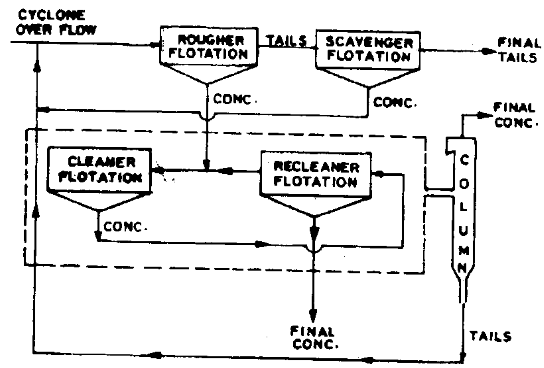


Fig. 2. Schematic flow diagram of MCP flotation circuit. (Dotted line portion of the circuit to be replaced by Flotation column)

3. EXPERIMENTAL PROCEDURE

Column test procedure suggested by earlier investigators[13] was followed. Initially, column was filled with water at desired airflow, wash water rate, feed-rate and froth depth. After stabilization with water, slurry conditioned with desired concentration of reagents was fed to the column through the feed pump. The column was allowed to run for at least three nominal residence times before sample collection. In order to check the steady state, tailing samples were collected at different time intervals and pulp densities of the same were measured. Once the pulp density of the tailings is constant, timed samples of feed, concentrate and tailings are collected with the help of automatic sampling valves. Immediately after sample collection, feed and wash water flow rates were checked and recorded. The collected samples were filtered, dried and weighed after measuring % solids. In some cases, all the feed samples collected over the day were mixed and a representative sample was taken for chemical analyses. Gas holdup was measured as per the procedure suggested by earlier investigators [8].

All experiments were conducted at respective plant site. Feed to the column was tapped from the appropriate stream of the flotation circuit of the plant.

4. CASE STUDIES

4.1. Beneficiation of copper ore

Malanjkhand Copper Project (MCP) of M/s HCL is one of the largest open pit base metal mine, designed to process 2.0 million tones per annum. Since the flotation response of oxides and secondary minerals was observed to be sluggish significant copper values are being lost in the tailings by conventional flotation. Also, final concentrate was found to be frequently contaminated with silica (above 11%) in the form of fines. Thus required grade and recovery could not be achieved by conventional flotation cells. It is generally known that acid insoluble (A.I) of above 11% in the concentrate are detrimental to flash smelter operation. The column was tried as cleaner cell and the results obtained were compared to that of plant performance. A few results of the campaign are shown in Table I.

Table I. Comparison of flotation results by column and conventional cells

S.No.	Chemical Assay (%)						Recovery (%)	
	Plant rougher conc.		Plant final conc. (Two stage cleaning)		Column conc. (single stage)			
	Cu	A.I	Cu	A.I	Cu	A.I	Plant	Column
1	28.5	21.2	29.0	11.3	30.4	4.0	92.0	94.9
2	21.8	22.3	25.0	14.0	28.1	3.2	94.0	98.0
3	16.2	42.1	30.0	20.2	32.4	3.7	79.0	89.9
4	20.0	31.1	22.0	19.0	29.5	2.7	78.0	86.9
5	22.3	26.6	28.0	10.8	29.9	2.6	92.0	90.4

Table II. Results of lead ore flotation by column

Plant feed assay (%) : Pb: 1.72 Zn: 11.74 Fe: 8.39

Rougher conc. assay (%) : Pb: 13.81 Zn: 9.01 Fe: 9.34

Description	Wt. %	Assay, % Pb	Zn	Fe	Recovery,%
Column conc. (1st stage)	31.0	41.47	7.38	11.01	94.5
Column Conc. (2nd Cleaning)*	70.2	49.49	7.58	4.68	98.8
Column conc. (2nd cleaning)**	56.8	76.89	4.82	2.89	93.1
Plant final conc.	-	40.21	5.70	9.74	-

(* without nigrosine, ** with nigrosine)

From the results, it is apparent that the quality of the concentrate obtained by single stage column cleaning is much superior compared to that of two-stage cleaning by conventional cells. Acid insoluble material in the final concentrate is drastically reduced to 2-4% from 14-20% by column as cleaner cell. The recoveries are also comparable to that of plant practice. Based on the in-plant trials, flotation circuit incorporating single cleaning by flotation column as shown in Fig. 2 was suggested to M/s HCL[14].

Other attendant benefits like savings in power, space and maintenance could be realized by adopting flotation column. Savings in transportation cost is more attractive in this particular case as the concentrates produced at MCP are to be transported to Khetri. Elimination of as much silica as possible in the final concentrate at plant site itself substantially reduces the transportation costs. If silica content in the concentrate is above 11%, accretions would build up on the walls of smelter. Frequent shut down of smelter due to above problem could be avoided by feeding clean concentrate with required SiO_2 content.

4.2 Beneficiation of Pb-Zn ore

Hindustan Zinc Limited (HZL) Udaipur, presently owned by Sterlite group of companies is continuously striving to provide enough zinc to meet India's requirements. A 3000 tpd lead-zinc beneficiation plant at Rampura-Agucha established by M/s HZL is one of the finest automated plants of its kind in India. The flotation circuit of lead consists of roughing and three stage cleaning and scavenging, while zinc concentrates are produced by four stages cleaning besides usual roughing and scavenging. Column flotation tests were conducted during 1992; both on lead and zinc circuits[15]. Flotation column was tried in the cleaning circuit of lead and zinc and the results of the same are tabulated in Table II and Table III.

In the case of lead circuit, two-stage cleaning was found to be essential to achieve high-grade lead concentrates. Since the pH conditions for depression of pyrite and

Table III. Comparison of results of zinc ore flotation by column and conventional cells

Description	Assay, %			Recovery,%
	Pb	Zn	Fe	
Column Feed	1.45	17.1	22.89	
Column Conc.	1.20	46.14	11.13	81.0
Column Tails	1.78	4.66	25.83	
Plant final conc.(Four cleanings)	0.93	39.50	12.85	-
Column feed	1.87	25.30	18.43	
Column conc.	1.17	56.51	8.15	82.0
Column tails	2.15	13.20	21.35	
Plant conc. (Four cleanings)	0.68	52.57	9.47	-

graphite are totally different (pH above 9.0 is to be maintained for the depression of pyrite, whereas pH less than 7 is required for graphite depression) it is difficult to eliminate both pyrite and graphite in a single stage operation. However, a clean concentrate assaying 76% of lead with minimum impurities was achieved by adopting two stage column cleaning.

In the case of zinc, a single stage cleaning was found to be sufficient compared to the existing practice of four- stage cleaning by conventional cells. Thus by adopting column technology, flotation circuit consisting of multi-stage cleaning by conventional cells could be compressed to a single stage cleaning. Furthermore, the complexity of the flotation circuit could be minimized without effecting the grade and recovery.

4.3 Beneficiation Complex Cu-Pb-Zn ore

The mineralogy of Ambaji multi-metal deposits owned by M/s Gujarat Mineral Development Corporation (GMDC) Limited is very complex compared to other deposits of similar kind. Copper, Lead and Zinc are the valuable minerals with siliceous gangue dominated by talc and mica. Several attempts were made to obtain individual concentrates and found that the level of zinc misplacement was high despite increased dosage of depressants. Because of high zinc activation and associated problems in copper lead separation, efforts were made only to produce bulk concentrate of Cu-Pb-Zn. The quality of the final bulk concentrate was often contaminated with talc/mica/oxidized minerals in spite of the addition of depressants for talc and mica. Hence column flotation technology was tried with an aim to achieve a bulk concentrate assaying 50% of Cu-Pb-Zn. Systematic tests were conducted by incorporating column in the cleaner circuit. Rougher concentrates generated by conventional flotation cells were fed to the flotation column and the results obtained are shown in Table IV.

From the results presented above, it is apparent that the concentrates obtained by column are superior compared to that of two-stage cleaning by conventional cells. Based on the results, a single stage column cleaning was suggested in place of existing two-stage cleaning by conventional cells to produce the bulk concentrates of Cu-Pb-Zn.

4.4 Iron ore beneficiation

The iron bearing minerals in Kudremukh ore body includes magnetite, marmatite, hematite, goethite and limonite with quartz as gangue mineral. Recovery of hydrous iron minerals was found to be poor due to high weathering. The silica content of the iron ore

Table IV. Flotation results of Cu-Pb-Zn bulk concentrates by column and conventional cells

Sample	Assay (%) Cu	Pb	Zn	Fe	TMC (%)	Recovery (%) Cu	Pb	Zn
1	1.42	10.64	38.50	5.89	50.56	56.50	72.95	77.43
2	1.60	11.87	37.10	6.28	50.57	56.70	72.76	72.23
3	1.46	10.20	37.90	5.83	49.60	61.89	73.89	79.83
4	1.69	11.79	38.00	6.12	51.48	60.11	75.16	77.05
5	1.57	10.52	39.10	5.91	51.13	62.82	73.69	79.92
6	2.00	14.78	35.70	7.10	52.48	77.54	87.52	67.33
7	2.17	11.88	36.60	7.07	50.64	86.08	92.0	90.11
Plant results								
8	1.97	11.68	33.30	8.09	46.95	79.01	79.45	88.36

Total Metal Content (TMC) = Cu+Pb+Zn

Table V. Results of reverse flotation of iron ores using column cell

S. No.	Assay, % Feed Total Fe	Conc. Total Fe	Conc. SiO_2	Tailings Total Fe	% Recovery
Column flotation results on rougher spiral concentrate					
1	51.48	65.23	2.97	6.03	97.28
2	51.48	65.77	2.26	7.56	96.39
3	52.09	65.89	2.07	8.09	96.33
4	52.09	65.61	1.90	9.78	95.45
5	54.98	65.81	2.71	4.84	98.44
Conventional flotation results on rougher spiral concentrate					
6	51.48	65.87	2.84	19.60	87.90
7	51.48	66.08	2.38	26.20	80.92
8	51.48	66.1	2.40	31.60	73.34
Column flotation results on feed to secondary magnetic separator					
9	61.57	68.16	1.65	15.98	96.72
10	61.57	68.48	1.32	19.16	95.64
11	63.31	68.31	2.05	34.08	92.14
Conventional flotation results on feed to secondary magnetic separator					
12	61.57	68.24	1.68	36.24	90.62
13	61.57	68.92	1.31	36.10	88.08
14	61.57	66.58	5.21	33.80	93.52

concentrates produced by M/s Kudremukh Iron Ore Company Ltd., (KIOCL), Kudremukh, by low intensity magnetic separator and Humphrey spirals is rather high to meet the specifications of the buyers. In order to compete in the world market, the company has decided to modify the flow sheet to produce concentrates assaying 2.5 to 3 % silica. Various beneficiation processes such as high intensity magnetic separation, hydraulic classification and flotation were extensively investigated. Among them reverse flotation of rougher concentrates obtained from rougher spirals was found to be most encouraging and techno-economically feasible[16]. Column flotation tests were conducted with an aim to improve iron recovery while maintaining the quality of the concentrates[17].

Table V gives the comparative results on two different feed materials. It may be noted that the quality of the concentrate is more or less similar both by conventional flotation and column flotation. However, better recoveries were obtained by flotation column. Loss of iron values into the tailings by conventional flotation was attributed mostly to the mechanical carry over of the fines with the siliceous gangue. The results clearly indicate that at least 10% higher recoveries could be achieved by adopting flotation columns

Table VI. Flotation results of column as cleaner cell in acid grade circuit

Sample	Assay %				Recovery %
	CaF_2	$CaCO_3$	SiO_2	P_2O_5	
1st Stage cleaning					
Feed	89.42	4.23	2.56	0.89	
Conc.	95.89	1.69	0.6	0.18	55.0
2nd Stage cleaning					
Feed	95.75	1.58	0.67	0.23	
Conc.	97.46	1.20	0.23	0.12	75.0
Conventional flotation (six stages of cleaning)					

Table VII. Flotation results of column in metallurgical grade circuit

Sample	Assay %				Recovery %
	CaF_2	$CaCO_3$	SiO_2	P_2O_5	
Feed	73.67	8.70	11.42	2.22	
Conc.	92.35	3.04	1.55	0.62	82.1
Feed	74.65	6.76	11.71	2.34	
Conc.	90.78	3.23	1.82	0.83	81.9
Feed	43.23	9.23	37.55	2.06	
Conc.	93.34	1.78	2.13	0.40	77.6
Conc.*	88.42	5.35	2.26	-	70.4

*Metallurgical concentrate of the plant

without affecting the quality of the concentrate. Encouraged by the column results M/s KIOCL has implemented column flotation technology to process their iron ore fines.

4.5 Beneficiation of Fluorspar

Considering the advantages and effectiveness of the flotation column M/s GMDC, has decided to investigate the beneficiation of fluorspar by column technology. The existing flotation circuit of acid-spar consists of roughing, scavenging and six stage cleaning. The tailings of first and second cleaner cells of acid spar circuit are subjected to roughing and three-stage cleaning to obtain metallurgical grade concentrate. Column was tried in the cleaner circuit and the results obtained are shown in Table VI and Table VII.

From the results it is apparent that the required metallurgical grade fluorspar could be achieved in single stage column cleaning compared to the roughing and three-stage cleaning by conventional cells. Similarly adopting columns as cleaner and re-cleaner in the place of existing multi-stage cleaning by conventional cells acid grade concentrates assaying above 97% of CaF2 could be achieved. By adopting three-column configuration as shown in Fig. 3, the yield of acid grade concentrate could be improved further. The results were confirmed by semi-commercial scale flotation columns. Thus by adopting three flotation columns, four stages of cleaning in acid grade circuit and four stages of cleaning in metallurgical grade circuit can be eliminated. Consequently complexity of the circuit and recirculation loads could be reduced. In the existing circuit, either depressants or collector is added at every stage of flotation to depress the gangue and to augment the dilution effects. It was observed that the concentrate quality obtained by three-stage cleaning by conventional cells could be achieved in single stage cleaning by flotation column. Because of this, re-circulation loads and dilution effects could be minimized. Consequently, reagent consumption could be minimized. In this particular case, reagent consumption was brought down by 25% using flotation columns[18]. Thus the overall economics of the production could be improved to sustain the global competition.

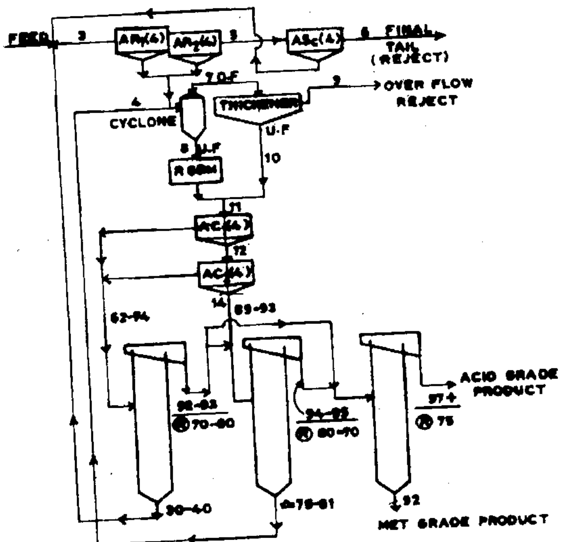


Fig. 3. Schematic proposed flotation flow sheet of fluorspar beneficiation

4.6 Beneficiation Gold ore

Beneficiation studies were carried out on the sulphidic gold ore samples of M/s Bharat Gold Mines Ltd., Kolar Gold Fields. At optimum reagent dosages and optimum column parameters[19] the column was operated continuously and the results obtained were shown in Table VIII.

Though the recoveries of column and conventional cells remain identical, the quality of the concentrate was found to be superior by flotation column. Weight of the concentrate solids (4%) obtained by column, is highly attractive compared to that of 29% by conventional flotation. Thus most of the gangue can be eliminated using column flotation. Consequently, cyanide consumption could be reduced in downstream operations.

Table VIII. Typical comparison of laboratory column results and the plant performance

S. No.	Laboratory column			Flotation plant		
	Conc. wt.%	Conc. Grade % Au	Recovery % Au	Conc. wt.%	Conc. Grade % Au	Recovery % Au
1	2.4	56.0	87.4	22.3	16.0	89.3
2	2.7	53.8	87.4	23.9	9.4	86.6
3	3.2	60.0	80.0	25.5	6.6	84.0
4	2.1	55.1	82.6	28.3	5.0	73.1
5	4.1	52.0	80.0	38.4	5.6	80.7
6	5.2	58.0	75.5	39.7	12.0	95.2
7	4.1	56.0	79.0	12.2	30.0	91.2
8	5.4	46.0	80.2	48.3	10.0	96.6
9	5.5	50.0	74.5	14.3	7.5	71.4
10	5.4	44.0	77.6	30.0	4.3	76.0
11	3.3	44.0	78.9	30.6	12.4	81.5
12	6.1	44.0	84.0	35.4	15.0	96.4
Avg.	4.13	51.58	80.6	29.08	11.15	85.16

Encouraged by the performance of the laboratory column over conventional flotation cells, semi-commercial column was installed in the flotation circuit and operated continuously at the optimum conditions established by laboratory size flotation column. The results obtained by semi-commercial column are compared to that of laboratory flotation column and conventional cells Figures 4 and 5. It is apparent that slightly better recoveries obtained in semi-commercial column may be due to close circuit operation where in the scavenger concentrate is recirculated. A good agreement of the results is seen from the contours drawn from the set of tests. In both the cases gold concentrates ranging from 35 to 60 ppm of gold with a recovery ranging from 70 to 90% was achieved. A similar agreement of results could be seen from Fig. 5, where concentrate weight is compared with gold recovery. The weight of the concentrates obtained by column flotation was found to vary from 2 to 10% which is very low compared to conventional flotation where the

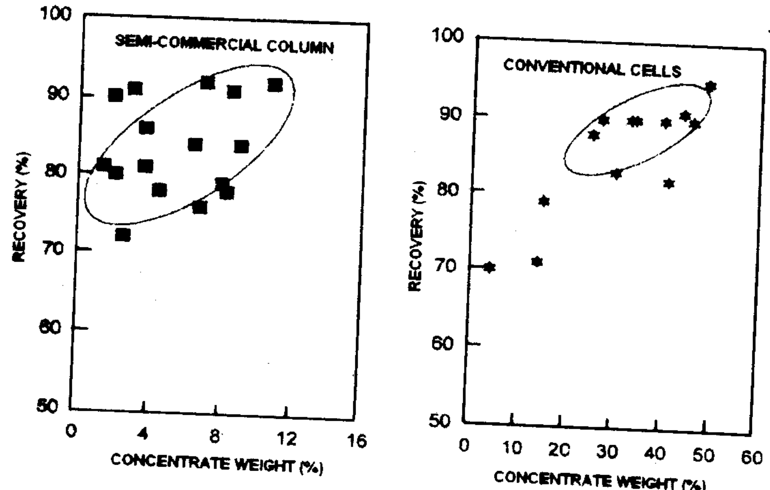


Fig. 4. Concentrate weight and recovery profile of gold ore by column and conventional cells

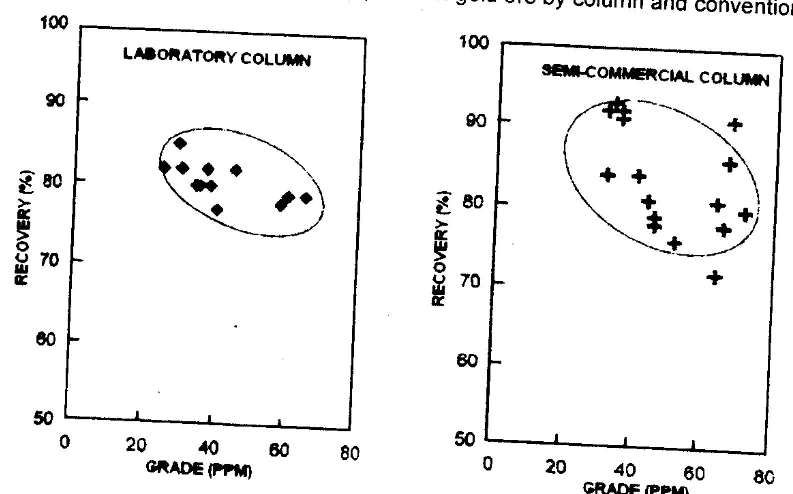


Fig. 5. Grade and recovery profile of gold ore by laboratory and semi-commercial scale flotation columns

concentrate weight was observed to fluctuate between 40 to 50%. High concentrates with minimum gangue obtained by flotation columns were attributed to wash water. It is known that wash water in flotation columns could effectively displace the entrained hydrophilic gangue particles from the froth phase[20].

4.7 Beneficiation of Sillimanite by semi-commercial flotation column

Indian Rare Earths Ltd., (IREL) is a leading producer of beach sand minerals and chemicals in our country. Optical microscope and XRD examinations of the placer sand samples of IREL, Chatrapur, Orissa, revealed the presence of ilmanite, garnet, sillimanite, rutile, monozite, zircon with small amounts of hematite, magnetite, hornblende, diopside, sphene, tourmaline and epidote. The grains vary from 53 microns to as coarse as 1000 microns and are mostly free from interlocking. The mined sand in a slurry form is pumped to a pre-concentration unit where heavy minerals are separated as concentrate and light minerals like silica and quartz are pumped back to refill the mine. The concentrate thus obtained from dredge and wet concentrator plants contain about 90% heavy minerals, which are subsequently separated by various physical separation techniques.

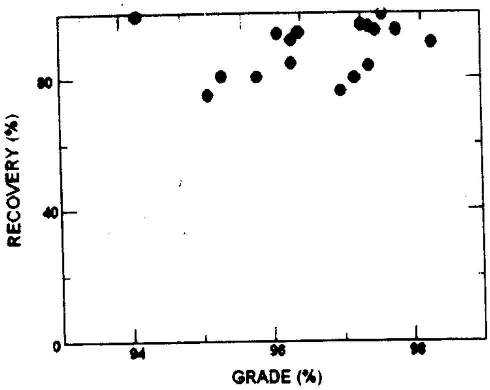


Fig. 6. Grade recovery profile of sillimanite by semi-commercial flotation column

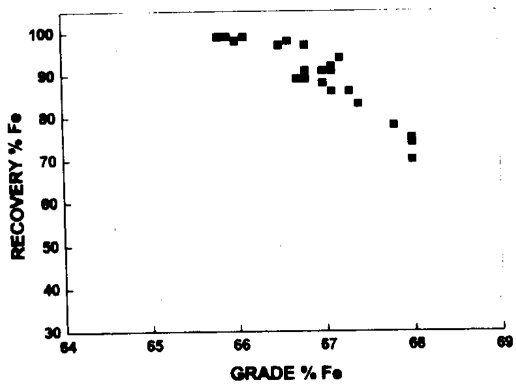


Fig. 7. Grade-recovery of iron ore by semi-commercial column

Table IX. Column flotation test results on different iron ore samples

S. No.	Feed assay (%)			Conc. assay (%)			Tails	Fe %
	Fe	Al_2O_3	SiO_2	Fe	Al_2O_3	SiO_2	Fe (%)	Recovery
1	65.5	1.24	1.79	66.9	0.87	1.50	54.9	90.2
2	64.8	1.51	2.82	66.7	1.15	0.62	59.5	75.8
3	66.7	1.36	1.99	67.4	1.04	0.90	56.7	94.4
4	67.0	1.14	1.18	68.1	0.86	0.59	61.2	84.5
5	66.1	1.51	3.03	66.8	1.16	1.68	42.4	98.2
6	63.6	1.49	5.26	67.0	1.16	1.48	-	96.3
7	64.9	1.38	3.36	66.4	1.49	1.29	31.6	97.9
8	66.0	1.24	2.21	67.2	1.09	0.86	58.6	87.6
9	65.7	0.93	2.73	67.6	0.77	0.91	58.6	81.1
1	66.4	1.28	1.67	67.2	1.10	0.71	55.7	94.2
11	65.0	1.44	3.03	66.7	1.22	1.49	54.8	88.0

At optimum conditions, continuous column flotation tests were conducted and the results of the same are plotted in Fig. 6. The results clearly indicate that 97% pure sillimanite with an average recovery of 90% could be achieved by flotation column. Quartz content in the final concentrate was brought down to less than 1% from an initial average value of 26%. Rutile content was reduced to 0.2% from its initial value of 2% and zircon content was brought down to 1.5% from its initial value of 4%.

4.8 Beneficiation of Goan iron ores by semi-commercial column

Iron ores of Goan origin are generally low grade and require beneficiation in order to meet the market requirements. Since alumina exists as fine clay and adherent material interspersed in ore body and in some cases both silica and alumina interlocked with iron ore particles, their removal by conventional methods was observed to be difficult. It is generally known that the adverse alumina to silica ratio is detrimental to blast furnace and as well as sinter plant productivity. Physical separation methods are found to be inadequate to process fine particles. M/s Sociedade De Fomento Industrial Ltd., Goa, are able to produce concentrates of 65-66% Fe from their non-mag circuits after installing HGMS. With an aim to achieve further enrichment, NML Madras Centre has conducted systematic column flotation studies by installing semi-commercial flotation column at their Greater Ferromet beneficiation plant[21]. The results obtained are shown in Table IX and Fig. 7.

Results presented above, clearly suggest the amenability of the flotation column for the beneficiation of iron ores of M/s Fomento. Iron ore concentrates assaying about 67% of

Fe and around 2% of SiO_2 and Al_2O_3 (combined together) could be achieved with a recovery of 85-90% in a single stage column flotation.

5. CONCLUSIONS

NML Madras Centre has developed indigenous flotation columns both laboratory size and semi-commercial unit for processing of low grade finely disseminated ores. State-of- the-art instrumentation was incorporated to facilitate automatic operation. Internal spargers developed by NML Madras Centre were used in both the systems. The systems were extensively field tested in the flotation circuits of various mineral processing plants of our country and found to be working satisfactorily. Detailed column flotation campaigns were conducted at Malanjkhand copper beneficiation plant, Rampura - Agucha lead-zinc beneficiation plant, Ambaji multi-metal deposit at Ambaji, Kadipani fluorspar beneficiation plant, Kudremukh Iron ore beneficiation plant, Greater Ferromet, Goa, gold ore beneficiation plant at Kolar Gold Fields and sillimanite beneficiation plant at Chatrapur. Flotation columns have shown definite advantage over conventional flotation cells in achieving better recoveries and grades.

- Acid Insolubles in copper concentrates remained as high as 11% in spite of two-stage cleaning by conventional flotation cells. Where as high-grade copper concentrates with less than 4% silica were achieved in a single stage column cleaning.
- Lead sulfide concentrates assaying above 70% Pb were achieved in a two stage column cleaning. Similarly, zinc concentrates assaying 55% Zn were obtained in a single stage column cleaning whereas it took four-stage cleaning by conventional cells.
- Column flotation was found to be amenable to produce bulk concentrates of Cu-Pb-Zn with a total metal content of 50% in a single stage column cleaning.
- It was demonstrated that fluorspar concentrates assaying 97% of CaF_2 could be produced by adopting three-column configuration. However, it requires several stages of cleaning by conventional cells.
- Gold concentrate assaying 50 ppm of Au was achieved by using flotation column as rougher cum cleaner cell. Whereas concentrates assaying 10 ppm of gold were generated by conventional flotation cells.
- Iron ore concentrates assaying around 2% of alumina and silica that are suitable for direct reduction process could be obtained by adopting flotation column.
- Quartz content in the final concentrate of sillimanite was reduced to less than 1% from its initial average value of 26% in a single stage column cleaning (rougher cum cleaner cum scavenger).

In general column flotation technology was found to be more effective to achieve high quality concentrates with minimum cleaning stages. Results clearly suggest that flotation column is effective both for cleaning operations and rougher cum scavenging purpose. While the counter current flow of particles and air bubbles along with long cleaning zone of column ensure good recoveries, wash water mechanism provides better enrichment and thereby grade of the concentrate. Wash water mechanism not only minimizes the hydraulic entrainment but also helps in selective rejection of less hydrophobic particles. Thus flotation column guarantee the product quality and also safeguard the recovery. Initially columns were adopted only in cleaning circuit with a view to improve the quality of the concentrate. Of late in our country, M/s. Tamilnadu Minerals (TAMIN) have implemented all column configuration for graphite beneficiation at Sivaganga and M/s KIOCL have implemented flotation column as rougher-cum-cleaner at their iron ore beneficiation plant situated at Kudremukh. In a recent innovation, Multotec Company based in South Africa developed the "Turbo Column" exclusively for rougher operations. Flotation columns are being implemented for all operations in newly commissioned flotation plants. Existing beneficiation plants as part of their modernization have incorporated flotation columns only for cleaning operations. However, the strategy of implementation of flotation columns is based on the lowest operating and capital cost with minimum technical risk.

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