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COPPER FLOTATION PROFIT AND CONTROL SYSTEM ACCURACY

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Abstract. The copper flotation profit can be estimated online utilising the assay of the on-stream analysers. Upper and lower limits of the profit can be calculated and the range between limits used for evaluation of the return on investment, the investment that has to be done in implementation project of new controls or analyser. The range depends on target values for concentrate and tailings and on the accuracy of controls and analyser. The separate pay-back values from improvement of the controls is estimated and improvement of the analyser measurements accuracy. The economic effect from improvement is analysed from the data collected from two flotation plants.

KeyWords. Mineral processing, analyser accuracy, profit evaluation.

1. INTRODUCTION

Considerable economic profit achieved in flotation processes control has been reported (Edwards, 19994; Miettunen, 1982; 1989). However, every control improvement is not cost-effective. The economic effect depends on many factors. Most of them can be evaluated simply, others like the economic effect of improvement of accuracy of controls an analyser is complicated to evaluate. The accuracy is crucial in the flotation processes control because they are poorly observable and controllable. The return on investment of new controls or analyser depends strongly on accuracy.

It is usual technique (Friedmann, 1995) to presume that the profit can be increased 1-2% in the result of implementation of new controls or analyser. The two percent level is chosen in (Cooper, 1980) as a "typical value" for cooper flotation processes. Starting from that value a complete economic analyses is reported and the play-backs of two X-ray analysers is evaluated. The final results obtained there are in direct dependence on the initial percent values.

It is shown in this paper that the initial percent values can be estimated from cooper flotation process, directly. These values are depend on process state in overall and are very different for different processes. Using the proposed method the economic effect of control improvement can be evaluated adequate to real processes.

The purpose of the paper is to evaluate the return on investment that one probably has in implementation of new controls in a copper flotation process and partially in implementation of a more accurate X-ray analyser like "Courier" or "Amdel" analysers.

In the case of implementation one can stabilise the flotation process more close to the setpoint with high profit. The profit can be increase using new target values for concentrate and tailings and/or using more accurate controls.

The upper and lower limits of the profit can be calculated for exact and real controls, the lower limit in dependence on control system accuracy. The difference between limits can be considered as the maximum return on investment or pay-back that one can achieve in exact control.

In real control case it is not possible to stabilise the process completely. Some part of the maximum pay-back can be obtained. The lower pay-back is stipulated by many factors. An inaccuracy of X-ray analysers is one of them.

A control system accuracy can be decomposed into the regulator and analyser accuracy. The control system accuracy is equal to analyser accuracy in the case of exact control. Upper and lower limits of the profit can be calculated in this control case and used for evaluation of the losses that one probably has in the case of implementation a real analyser. The return on investment is lower on the value of these losses in the case of real analyser.

In these more or less idealistic assumptions a clear-cut result can be shown. An economical performance of the copper flotation processes cannot be improved without improvement of the control and measurement system accuracy.

It is shown also that the copper flotation profit can be estimated online by assay analysis in ore-feed, concentrate and tailings. That is a new application of the X-ray analysers in evaluation of the performance of cooper flotation processes by economics.

Finally, a simple control algorithm is proposed for stabilisation of cooper flotation processes on the basis of mass balance relationship.

2. MAIN RESULTS

The copper flotation profit depends on control system accuracy as a complex function. It can be determined as a numerical function by statistical and economic analysis of some real processes. The following typical situation was withdrawn in these analysis from the flotation processes in two factories.

1. Profit of control improvement. The copper flotation profits calculated per 1 ton of ore-feed for Concentrators A and B are shown* in Table 1 as well as the maximum profits that can be achieved in limit by implementation of exact controls. It is assumed that the exact controls are able to stabilise any deviation of the process from setpoint. A real control system is able to stabilise the process incompletely and because of that has some loss in profit. Usually, 30-50% of the variation can be reduced in industrial applications. The same percentage of ideal pay-back is realistic to save in implementation of real controls. The ideal and real pay-backs calculated from difference of exact and real controls are shown in Table 1. They are calculated in the assumption that both grades for concentrate and tailings can be stabilised at target values for any variation of ore-feed.

The cooper flotation profit is about 3-times higher for Concentrator A. The profit depends on specialisation of factories. The copper is the main product in Factory A and a co-product in Factory B. It also depends on mine (ore-feed), flotation circuit and on automation. The Concentrators A and B are very different by these factors and especial by automation level. An automatic control system is used on Concentrator A and manual control on Concentrator B. The profit level is higher on Concentrator A, but the return on investment is lower there (see Table 1). The profit in maximum can be increased 1.2% (real: 0.4-0.6%) on Concentrator A and 10% (real: 3-5%) on Concentrator B. The increase of profit depends on state of the flotation processes. The state of the processes A and B recorded in 10 days period is shown in Figs 1, 2.

Table 1. Copper flotation profit in two factories. Pay-back from implementation of exact controls.

	Real stabilisation	Ideal stabilisation
Concentrator: A Profit, USD/ton(feed) Pay-back: ideal real, mUSD/year	 7.505 0.77-1.15	 7.591 **2.304**
Concentrator: B Profit Pay-back: ideal real	 2.210 2.85-4.27	 2.428 **8.541**

2. Profit in incomplete stabilisation. The profit is lower if the control system is implemented only for one of the processes: for concentrate or tailings. The following can be concluded from decomposition of the pay-back between these two processes (see Table 2).

The tailings control is a more cost-effective than concentrate control on Concentrator A. The best results can be obtained by control of both these processes. The control of tailings and concentrate processes are equally essential on Concentrator B and also control of both these processes, but more essential than on Concentrator A.

3. Cost of inaccuracy. The maximum profit cannot be achieved in practice because of inaccuracy of controls. The losses in profit can be decomposed into the losses for regulator and analyser. The losses of two X-ray analysers are shown in Table 3 in dependence on measurements accuracy for "Courier" and "Amdel" analysers. The losses of profit is about 2-times lower for "Courier" analyser than for "Amdel".

4. Cost-effective measurements. Accuracy of measurement depends on range of analyser. It is higher in concentrate and lower in tailings analysis. One can more benefit from that situation on the Concentrator A as the concentrate measurements there are more cost-effective than tailings measurements (Table 4).

5. Profitable target. In some application the flotation process efficiency can be increased special, after renovation of the process. Sometimes it is possible to run the process at a new higher target level for concentrate and lower level for tailings without affecting on flows. More

* The profit level is confidential, fictitious values are reported, losses and pay-backs are real.

cooper can be recovered and profit obtained (Table 5), that is because of renovation of the process, may be with new analyser. It is usual practice that a new higher concentrate level will be set up as target in the case of implementation of a new more accurate analyser.

Table 2. Pay-back of exact controls for concentrate and tailings separately.

Processes under ideal stabilisation	Processes under real stabilisation	Target, %Cu	Standard deviation	Profit USD/t	Pay-back mUSD
Concentrator: A					
Tailings	Concentrate	25.5	0.776	7.550	1.200
Concentrate	Tailings	0.074	0.019	7.526	0.564
Both	Neither			7.591	2.315
Neither	Both			7.505	0
Concentrator: B					
Tailings	Concentrate	21.7	2.47	2.408	7.756
Concentrate	Tailings	0.114	0.022	2.379	6.614
Both	Neither			2.428	8.541
Neither	Both			2.210	0

Table 3. Cost of inaccuracy of X-ray analysers.

	Ideal measurements	"Courier" accuracy	Double "Courier" accuracy	Half "Courier" accuracy	"Amdel" accuracy
Stand deviation:					
Ore-feed	0	0.032	0.016	0.064	0.074
Concentrate	0	0.95	0.475	1.90	0.95
Tailings	0	0.011	0.006	0.022	0.044
Concentrator: A					
Profit, USD	7.591	7.513	7.569	7.397	7.373
Losses, mUSD	0	2.085	0.591	5.191	5.838
Concentrator: B					
Profit	2.428	2.349	2.404	2.234	2.261
Losses	0	3.089	0.950	7.599	6.567
Pay-back: ideal	8.541	5.452	7.591	0.942	1.974
real, mUSD	2.85-4.27	1.82-2.73	2.53-3.80	0.31-0.47	0.66-0.99

Table 4. Cost of inaccuracy for concentrate and tailings, separately (for "Courier" analyser).

Processes under ideal analysis	Processes under real analysis	Profit USD/t	Losses mUSD
Concentrator: A			
Concentrate	Tailings	7.542	1.302
Tailings	Concentrate	7.558	0.879
Neither	Both	7.513	2.095
Both	Neither	7.591	0
Concentrator: B			
Concentrate	Tailings	2.398	1.162
Tailings	Concentrate	2.380	1.868
Neither	Both	2.349	3.089
Both	Neither	2.428	0

Table 5. Pay-back of flotation at a higher for concentrate and lower for tailings level (for Concentrator B).

New target	Increase %Cu	Profit USD/t	Pay-back mUSD	Pay-back of exact control
Concen.				
21.7	0	2.210	0	+8.541
22.2	0.5	2.411	7.870	
22.7	1.0	2.608	15.622	
23.7	2.0	2.985	30.592	
Tailings				
0.114	0	2.210	0	+8.541
0.109	0.005	2.240	1.154	
0.104	0.010	2.267	2.210	
0.094	0.020	2.326	4.522	

6. Control law. The difference between ideal and real pay-backs can be kept minimal if an automatic control system is used for stabilisation of the concentrate and tailings processes close to target levels. The minimum variation control can be expressed (see Section 5) as the following control law:

$$u = \frac{b_1 b_0 + \nu_1 \nu_0 - B_{01}}{b_1^2 + \nu_1^2 + B_1} \qquad (1)$$

where u - control: ratio $u = Q_T/Q_C$ between Q_T - tailings and Q_F - concentrate mass-flows, ton/day,

b_1, b_0 - difference between measured processes:
$b_0 = \xi_C - \xi_O$ - between ore-feed and tailings grades,
$b_1 = \xi_O - \xi_T$ - between concentrate and tailings grades,

ν_0, ν_1 - difference between target values:
$\nu_0 = \Theta_C - \Theta_O$ - between ore-feed and tailings grades,
$\nu_1 = \Theta_O - \Theta_T$ - between concentrate and tailings grades,

B_{10} - variation of errors in tailings measurements,
B_1 - sum of the variations of errors in concentrate and tailings measurements.

7. Total cost. The final pay-back is lower than calculated by this method. The cost of equipment, installation and operating expenses must be included in calculation of the capital investment.

8. Online observable profit. The profit can be estimated online using any X-ray analyser. It is important for operator to know the economic performance of process in real time. The copper flotation profit can be estimated in every 10 minutes and in average per hour or per sift. It is not simple to observe the flotation process economics directly from measurements. Compare the profit (Figs 3, 4) and measured processes (Figs 1, 2). The profit is affected most strongly with ore grade in Factory A and with concentrate grade in Factory B.

The estimated profit as a stochastic function is not well defined and as a dynamic process not stable as well. That is because the profit is estimated from inaccurate measurements. Certain "smoothing" of the estimated data is necessary in practical calculations.

Monte-Carlo method was applied in profit analysis (see Section 3) and a simple profit-function (Section 4) was used.

3. PROFIT ANALYSES: METHOD

Assume that profit P depends on process state θ as a convex function P(θ) and that the concentrate and tailings grades are stabilised around some average value M{θ} that is equal to target value Θ. A good profit P(Θ) can be obtained if the concentrate and tailings are stabilised exactly in target θ = Θ. This profit P(Θ) = P(M{θ}) cannot be obtained in average. The average profit is lower

$$M\{P(\theta)\} \le P(M\{\theta\})$$

That is a well known property for convex functions. The difference in profit values

$$L = P(M\{\theta\}) - M\{P(\theta)\}$$

can be considered as a loss that one has in the case of real control. It can be considered as pay-back in the case of exact control. Usually, the loss and pay-back are calculated as annual values (per year) in economic analysis.

The highest profit (in average) can be obtained as a theoretical limit in the assumption that true measurements and ideal regulator are in use

$$M\{P(\theta)\} = P(M\{\theta\}).$$

Using Monte-Carlo method, the initial distribution π(θ) of the state can be converted into the distribution for profit $\pi_1(P)$. Both values: mean or median of the distribution can be used for characterisation of the typical profit values that most likely can be expect in control of real process.

The following scheme was used in numerical analysis of the relationship between profit and control system accuracy and measurement system accuracy:

θ = Target + Error,

$\pi(\theta) = IN(\Theta,\sigma) \rightarrow \pi_1(P) \rightarrow \text{Median}\{\pi_1\}$.

Here IN(Θ,σ) - independent Gaussian distribution with mean Θ and standard deviation σ. The latter parameter was determined as an accuracy of considered X-ray analysers and accuracy of used controls.

The stochastic modifications of real processes on Concentrators A and B were used in calculations. These modifications are equal to real processes by distribution; they are equal approximately as the real distribution was a little different from normal and the sample size for simulation was chosen large enough (5000) for quick analyses but not to eliminate the sampling errors completely.

4. PROFIT AS A FUNCTION

The cooper flotation profit can be defined in several modifications. In the simplest case it can be calculated as the function that depend on

C_{market} - copper market price, USD/ton,
Q - annual production of cooper concentrate, ton,

costs of
C_{refin} - refining, USD/ton,
C_{smelt} - smelting,
C_{trans} - transportation,
C_{oper} - operating, per ton

and on the flotation process state, like grades of
θ_O - ore-feed, Cu%,
θ_C - concentrate and θ_T - tailings.

The profit can be calculated from mass balance and cooper prise for concentrate as follows:

1. Mass balance of water and cooper

$$Q_F = Q_C + Q_T, \quad \theta_O Q_F = \theta_C Q_C + \theta_T Q_T. \qquad (2)$$

Here Q_F, Q_C, Q_T - mass-flows, ton/day:
Q_F - ore feeding,
Q_C - concentrate production,
Q_T - tailings removal.

The mass balance (2) can be expressed as ratio

$$\frac{\theta_O - \theta_T}{\theta_C - \theta_T} = \frac{Q_C}{Q_F}. \qquad (3)$$

2. Cooper price per ton concentrate, USD/ton,

$$C = \frac{\theta_C - 1}{100}(C_{market} - C_{refin}) - C_{smelt} - C_{trans}.$$

3. Cooper flotation profit per ton of ore-feed, USD/ton,

$$P = (C - C_{oper})\frac{Q_C}{Q_F}. \qquad (4)$$

4. Annual profit, USD,

$$P_{Annual} = \eta Q P,$$

where η - ratio of average grades: $\eta = M\theta_C/M\theta_O$ - concentrate to ore-feed.

The profit depends on concentrate and tailings as a convex function. In a small variation range it depends on ore grade nearly as a linear function and on concentrate grade as a negative hyperbolic function,

$$P = \frac{\theta_O - \theta_T}{\theta_C - \theta_T}\left(\left(\frac{\theta_C - 1}{100}a_1 - a_2\right) - a_3\right) \approx a_1\theta_O - a_4\frac{\theta_O}{\theta_C},$$

and on tailings grade as a degreasing linear function,

$$P \approx \frac{\theta_O - \theta_T}{\theta_C} a_4.$$

Here a_1,.., a_4 - constants, they are independent of state.

The cooper can be a single product of factory or one of many other metals produced on factory. In the latter multi-product case the cooper grades in tailings are more cost-effective than shown in (4), especially if expensive reagents are used to recover valuable metals in tailings. For example, the cyanide is used to recover the gold in tailings. This leaching operation is an expensive due to consumption of cyanide in considerable amounts, especially if the cooper grade in tailings is high.

The leaching expenses can be accounted for in the profit function through the term $C_{leach}\,\theta_T$ that can be added to (4) if the tailings grade is higher than target value $\theta_T < \theta_T$. In this case the profit function is more dependent on tailings as the cost C_{leach} of cyanide leaching is high.

Initial parameters. The following example of initial data was used in profit calculations:

Q = 1 000 000 ton - annual production,
C_{market} = 2667 USD/ton - copper market price,
C_{refin} = 28 USD/ton - refining cost,
C_{smelt} = 127 USD/ton - smelting cost,
C_{trans} = 20 USD/ton - transportation cost,
C_{oper} = 280 USD/ton - operating cost,
C_{leach} = 18 USD/ton(tails) - cost of cyanide leaching,
η = 26.7 (Concentrator A), 39.3 (B) - ratios: concentrate to ore-feed.

5. CONTROL LAW

The cooper flotation process is a stochastic partially observable process that depends on many parameters which are mostly uncontrollable. However, a real flotation process is stable, it has a slow dynamics as affected by large masses. The profit as a dynamic stochastic process is a less stable (see Figs 3, 4). That is because the profit is not a well-defined stochastic function, as a ratio its statistical properties are poor and dynamics complicated. To see some complications calculate the first moment of the profit function and the dynamics of profit process (by Ito rule) in the simplest assumptions of normal distribution and linear state processes, for example.

The profit process is not applicable for control, its direct use in stabilisation will be ineffective. Better results can be obtained in indirect control, by stabilisation of the state processes for concentrate and tailings on some target values. The control problem in this case can be stated and solved as the following.

Consider ratio Q_T/Q_C as a control parameter and the relationship (2) as the model of process written in a compact form as

$$\beta_0 - \beta_1 u = 0, \qquad (5)$$

where u - control: $u = Q_T/Q_C$,
β_0, β_1 - differences: $\beta_0 = \theta_C - \theta_O$, $\beta_1 = \theta_O - \theta_T$.

The following relationship is similar to (5) but for target values

$$\nu_0 - \nu_1 u = 0, \qquad (6)$$

where ν_0, ν_1 - differences: $\nu_0 = \Theta_C - \Theta_O$, $\nu_1 = \Theta_O - \Theta_T$. Θ_O, Θ_C, Θ_T - target values.

Stabilisation of the mass balances for both measured (5) and reference (6) processes can be considered as a purpose for control. In this case the control problem can be stated as the following square function minimising problem

$$v^u = \mathbf{M}\{(\beta_0 - \beta_1 u)^2 + (\nu_0 - \nu_1 u)^2\} \qquad (7)$$

subject to state (5) and reference (6) processes.

That is simple to prove that solution of the problem (5)-(7) can be expressed in the following form:

$$u = \frac{b_1 b_0 + \nu_1 \nu_0 - B_{01}}{b_1^2 + \nu_1^2 + B_1},$$

where b_0, b_1 - current mean of state-dependent processes:

$$b_0 = \mathbf{M}\{\theta_C/F^\xi\} - \mathbf{M}\{\theta_O/F^\xi\}, \quad b_1 = \mathbf{M}\{\theta_O/F^\xi\} - \mathbf{M}\{\theta_T/F^\xi\},$$

B_1, B_{10} - covariance of estimation errors:

$$B_1 = \mathrm{Var}\{\theta_O/F^\xi\} - 2\mathrm{Cov}\{\theta_O,\theta_T/F^\xi\} + \mathrm{Var}\{\theta_T/F^\xi\},$$

$$B_{10} = \mathrm{Var}\{\theta_O/F^\xi\} + \mathrm{Cov}\{\theta_O,\theta_C/F^\xi\} - \mathrm{Cov}\{\theta_T,\theta_C/F^\xi\} - \mathrm{Cov}\{\theta_T,\theta_O/F^\xi\}.$$

These statistics can be calculated on the basis of available observations. The filtrated values of the measured processes can be used for exact calculations. The current measurements can be used in simplified calculations. In the latter case the mean values of b_0, b_1 can be calculated as the simple differences

$$b_0 = \xi_C - \xi_O, \quad b_1 = \xi_O - \xi_T.$$

and correlation between measurements can be ignored:

$$B_1 = \mathrm{Var}\{\theta_O/F^\xi\} + \mathrm{Var}\{\theta_T/F^\xi\}, \; B_{10} = \mathrm{Var}\{\theta_O/F^\xi\},$$

Variation of the measurement errors can be used for determination of the parameters B_1, B_{10}.

5. CONCLUSION

Usually, the profit is over- or under-estimated in economic calculations if presumed that profit can be increased 1-2% in control improvement. The real increment can be 5-times different from that (0.5-5%). The return on investment of the same controls or analyser is rather different in different flotation processes. The same analyser can be cost-effective in one process and not in another.

The profit is affected strongly by real target level for concentrate and tailings. The target depends on state of concentrator in overall and on its automation.

In a less essential scale the profit is affected by accuracy of controls and analyser used. The return on investments of new controls or analyser can be evaluated using ideas of Monte-Carlo simulation in the way shown in this paper. A final decision on a new control proposal can be made on the basis of these calculations.

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REFERENCES

Cooper, H.R. (1980). On-stream X-ray analysis. In *Flotation*. P. 865-894.

Edwards, R.P. (19994). XRF analysis in process control. J. *In Process*, Vol , No . P. 2-5.

Friedmann, P. (1995). *Economics of Control Improvement.* Instrument Society of America. North Carolina. 162 p.

Flintoff, B.C. (1992). Measurements issues in quality control. *Proc.* CMP Branch Meeting. P. 1-19.

Miettunen, J. (1982). The control strategy of zinc flotation at the Pyhäsalmi mine. *Proc.* SME 17th International Symp. on Application of Computers and Operations Research in the Mineral Industry. P. 675-665.

Mittunen, J. (1989). Expert system type support for the process operator. *Proc.* IFAC 6th Symp. on Automation in Mining, Mineral and Metal Processing. Buenos Aires, Vol. 1. P. 121-126.

STATE
of Concentrator A

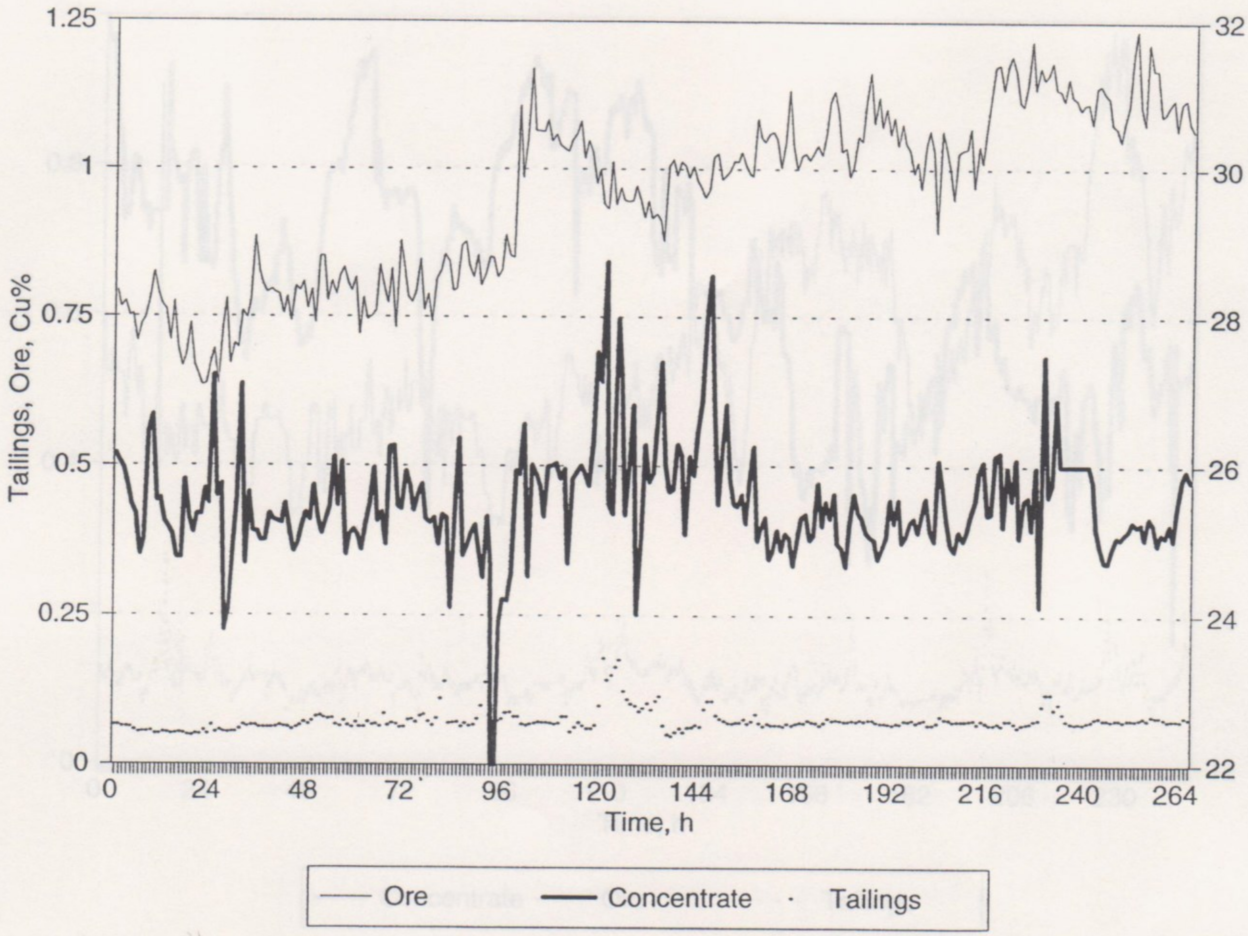

Fig. 1

STATE
of Concentrator B

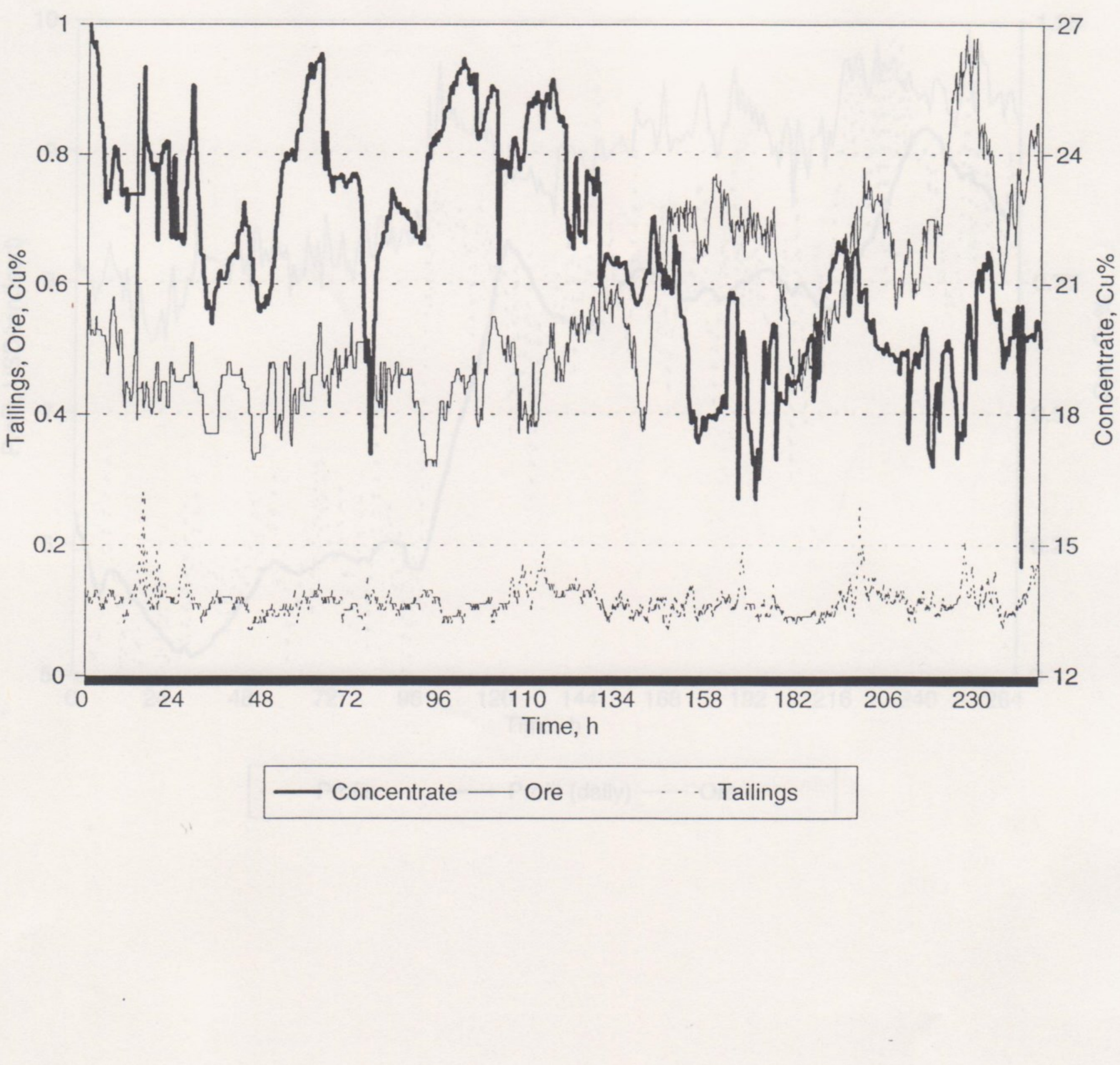

Fig. 2

PROFIT
on Concentrator A

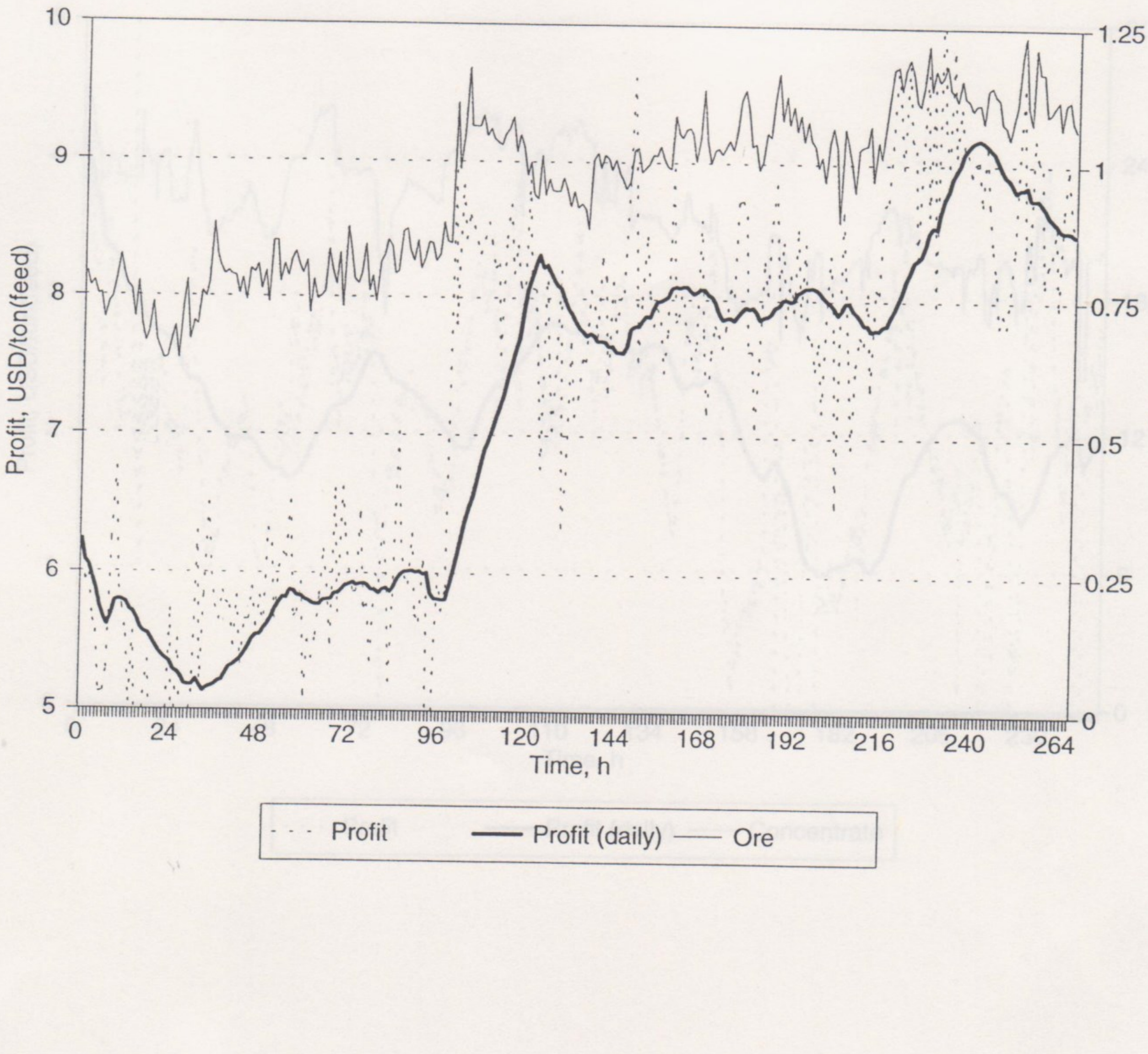

Fig. 3

PROFIT
on Concentrator B

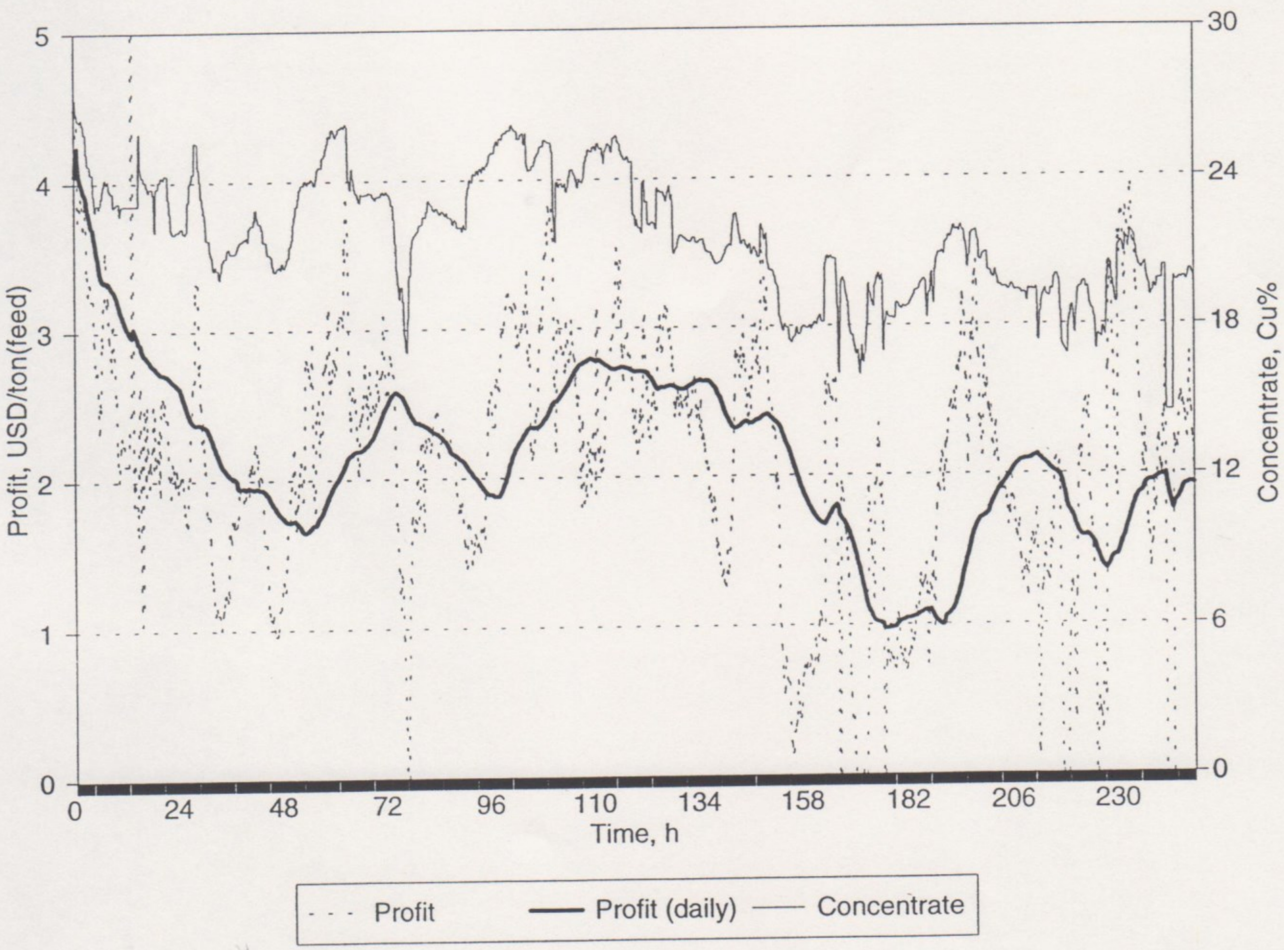

Fig. 4