AN OPERATIONAL MODEL FOR FROTH FLOTATION: APPLICATION TO THE COPPER INDUSTRY

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ABSTRACT

The "Operational Model" has been developed to provide a reliable link between the theoretical and practical aspects of mass concentration by froth flotation, specially in the case of continuous operations.

The model is based upon four principles and three mathematical laws which take into account the macroscopic phenomenon of mass transfer (migration of particles) inside a flotation cell. In addition, the application of the model permits the evaluation of the process by monitoring the flow of concentrate throughout the circuit. It also provides a set of operational actions to be taken in order to optimize the selectivity of a given flotation plant.

INTRODUCTION

Froth flotation is one of the most common mineral processing operations. The process involves the capture of small particles (hydrophobic particles) by air bubbles in the pulp phase, followed by their transport to the surface of the slurry, where they are collected in a froth.

As in other mineral processing operations, several factors make it difficult to obtain useful correlations between laboratory testing and continuous industrial operations. On the other hand, such correlations are usually more straightforward in chemical processes due to general accumulated knowledge on transport phenomena, for chemical processes are usually less dependent on scale-up relations.

This paper deals with the major aspects of the so-called Operational Model which has been developed in order to interpret, in a dynamic manner, the practical features of mass concentration by froth flotation, as well as other mineral processing unit operations (1). Besides its originality and simplicity, the model enables the establishment of a link between the basic phenomena that take place inside a flotation cell: the natural phenomenon (migration of particles) and the real phenomenon (mass concentration). The model, which is based upon four principles (conceptual definitions) and three laws (simple mathematical equations), becomes a useful tool in setting up a practicle criterion for scaling up the results from batch and semi-batch laboratory tests to continuous plant cells. In addition, the model provides a set of operational actions to be carried out in order to optimize existing circuits without new investments.

MACROPHENOMENOLOGICAL CONCEPT OF THE MODEL

Traditional approaches to modelling froth flotation using kinetic models are unable to fully represent the actual process of mass concentration. This occurs because these approaches tend to seek analogies with models used to describe chemical processes (2-5), when, in reality, the differences between the phenomena found in these two branches of engineering are evident, as shown in Table I.

NATURAL FLOTATION x REAL FLOTATION

Since flotation is the result of mass transport as a function of time, that is, according to the kinetics of the process, it can be defined as "Natural Flotation", while the actual process of mass concentration, based on experimental results, will be called "Real Flotation". By definition, flotation as a phenomenon is always natural, although the concentration process (real flotation) is in effect the result of operational actions. The fraction of mass actually removed from either a cell or bank of cells (fractional flotation) and the arrangement of a given flotation circuit are examples that illustrate the concepts of Real Flotation. The traditional interpretation of flotation has been restrained to Natural Flotation (3,6,7), in particular the kinetic models. These models, however, have found limited practical application in the scaling up of results, specially in case of fractional or closed loop circuits.

Let $\underline{m}$ be the amount of ore fed to a flotation cell. The transport of mass via flotation is equal to the rate of material removed from the cell:

$$\frac{dm}{dt} = - k \cdot m \,, \qquad\qquad (1)$$

TABLE I – Differences Between the Processes of Chemical
and Mineral Processing Operations

	Chemical	Mineral Processing
Phenomenon	Mass and Heat Transfer	Particle Size Reduction, Separation of Particles
Mass Transport	Mass Transfer between Phases (Diffusion)	Macromolecular Transport (migration of particles)
Phases	Usually Homogeneous (gas, liquid or solid)	Usually Heterogeneous (pulp, froth)
Transport Gradient	Concentration Gradient between Phases	External Action upon the Phenomenon forcing migration
Situation in Steady State	Continuous Gradient, no Intervention by the Operator	Natural Gradient; can be altered by External action
Principal Mechanism	Natural	Operational
Macroscopic Evaluation	Result = Process	Result ≠ Process

wherein k is the kinetic constant, as in an irreversible first order chemical reaction.

Let $\underline{C}$ be the mass of concentrate actually removed from the cell. Assuming ideal conditions of Real Flotation, one can set:

$$\frac{dC}{dt} = \frac{dm}{dt},$$ (2)

That is, the material floated is removed as concentrate at the same rate that it is produced. For a given period of time Δt:

$$C = k.m.\Delta t$$ (3)

Under these conditions, it is possible to carry out a quantitative analysis of the variables that affect Natural Flotation (8,9).

FIRST OPERATIONAL PRINCIPLE

"The amount of mass naturally floated is removed from the cell at a rate lower than the rate of its transfer from the pulp to the froth phase".

This is equivalent to state that

$$\frac{dC}{dt} < \frac{dm}{dt}$$ (4)

Some of the practical consequences of this first principle are listed below:
- not all the froth produced is concentrate; it is only the amount actually removed from the cell;
- since the conditions of operation in either a cell or bank of cells usually set a froth layer of about the same thickness, it follows that an amount of mass per unit time, $d(m-C)/dt$, enters the layer of froth and, as a result, an equivalent quantity of water is driven back to the pulp, pushing a certain amount of ore particles of low hydrophobicity. This, in turn, increases the percentage of solids in the froth phase, as shown schematically in Figure 1;
- in cleaner circuits, where the layer of froth is usually thicker, it happens that:
  . a simple first order kinetic expression is unable to fully describe the phenomenon of mass concentration;
  . a gradient of hydrophobicity inside the froth column occurs, causing another mechanism of mass concentration, the so-called cleaning action of froth column from the pulp/froth interface to the cell surface;
- under steady state conditions, the kinetic curve does not present the same pattern for continuous or batch operations.

SECOND OPERATIONAL PRINCIPLE

"The metallurgical recovery of a flotation operation is independent of the residence time for a given time greater than the minimum required by the natural phenomenon". In other words:

$$R \neq f(t), \text{ for } t > t_m,$$ (5)

wherein R is the metallurgical recovery and t_m the minimum time of the natural phenomenon.

Within certain limits, Real Flotation kinetics may present a rate profile different from that of the natural phenomenon. However, the selectivity of the operation remains the same, as indicated in Figure 2, where the kinetic curves of Real and Natural Flotation are schematically shown.

Some kinetic models (10,11) establish that by increasing the flotation time, a larger amount of material is floated, which is not necessarily observed, since the phenomenon is actually of mass concentration. In plant practice, the cleaning action of the froth column has a certain beneficial effect on the selectivity of the process for $t \gg t_m$. In a well operated circuit, the excess time is used to "refine" the froth layer, rather than acting on the natural phenomenon in the pulp phase, that is, it has no effect on the kinetics of the process.
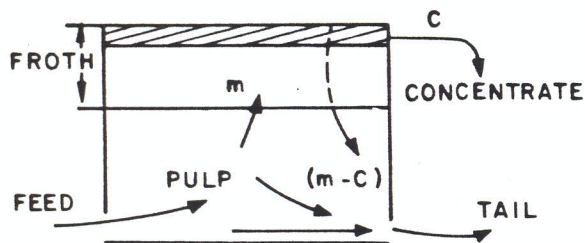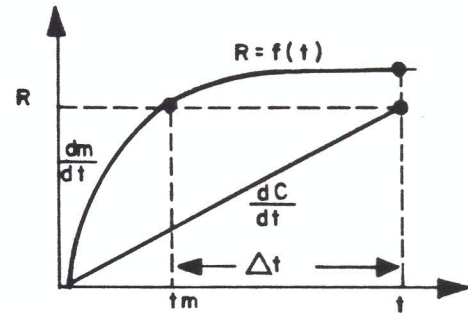
Figure 1 - Concentration Mechanism   Figure 2 - Kinetic Curve

FIRST OPERATIONAL LAW: THE LAW OF CONCENTRATION

The first operational law states that:

$$R = f(Rcm) \quad \text{for } t \geq t_m , \tag{6}$$

wherein R is the metallurgical recovery ($R = [C]/[A]$), and [A] and [C] are the distribution of the substance of interest in the feed and concentrate, respectively. A new term, the mass concentration ratio, Rcm, is defined, expressing the ratio of mass feed to that of concentrate:

$$Rcm = A/C \tag{7}$$

Equation (6) is called Selectivity Equation. The macroscopic aspects of flotation are a consequence of its utilization.

By plotting R versus Rcm, one obtains the selectivity curve, as shown in Figures 3 and 4. Referring to Figure 4, condition "A" is more selective, because:
- for the same amount of concentrated mass, the recovery is higher;
- to obtain the same recovery, less floated concentrate is required.

It is possible to correlate the selectivity curve obtained in laboratory testing to continuous plant operation data. The operational point (R,Rcm) chosen in laboratory can also be obtained in industrial practice, as long as the minimum flotation time is observed. Under certain practical limits, one can adjust the discharge valves or the air supply of a given cell, in order to generate the desired amount of concentrate.
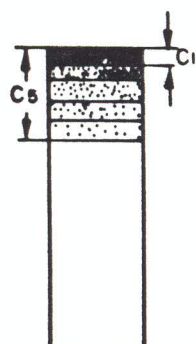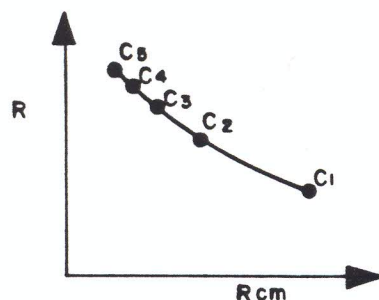
Figure 3 – Selectivity Curve

Figure 4 – Evaluation of the Selectivity

Example 1

To demonstrate the first two principles and the first operational law, the following example is presented. The experimental data are from a copper sulphide plant. Two different laboratory flotation experiments, using the same ore sample (actually the discharge from the ball mill) were carried out. The flotation time was 10 minutes for both tests, although the kinetic conditions (pulp agitation) varied. Intermediate samples were taken and analyzed. The results are indicated in Table II and graphically in Figure 5, which also shows a plot R vs. Rcm.

It can be seen that the R vs. Rcm selectivity curve is the same, regardless of the kinetic conditions, although the kinetic curves are obviously different. Thus the selectivity of the process is the same, although an analysis based on kinetic models would have led to two different conclusions. Figure 5 also shows the operational point (R = 93%, Rcm = 12) that corresponds to the project operating condition of the plant start-up, years before. The data indicate that the selectivity under which the ore is floated remains the same, provided the operational conditions (particle size, reagent consumption, etc.) are not changed.

TABLE II – Flotation of an Industrial Copper
Sulphide Slurry – Experimental Results

Time (min)	Product*	TEST 1		TEST 2	
		R (%)	Rcm	R (%)	Rcm
2.5	C_1	85.6	28.5	87.7	23.1
5.0	C_2	88.8	23.3	90.7	18.7
7.5	C_3	90.0	20.7	91.8	16,0
9.0	C_4	90.4	19.5	92.2	15.1
10.0	C_5	90.7	18.7	92.3	14.6

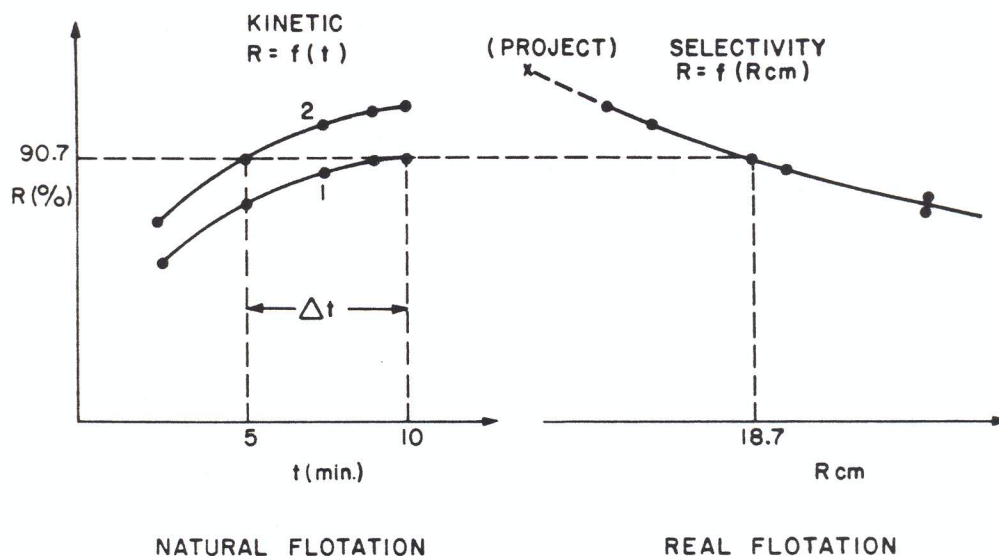* C_1 to C_5 are the final concentrates as in Figure 3

Figure 5 - Experimental Results, Example 1

FLOTATION UNDER STEADY STATE CONDITIONS

In continuous flotation operations, the natural behaviour of the process depends on operational features to a certain extent: different air supply, froth layer thickness, pulp density, etc. A process with more than one stage (e.g., rougher + cleaner) is therefore the result of the "naturalness" of the phenomenon (hydrophobic particles) and operational actions, so that a "real" relationship between the stages is set.

The main objective of the second part of this model is to provide answers to the following important questions:
- How much concentrate shall be floated?
- Which recovery is to be achieved in each stage?
- How many stages are necessary?
- What happens to the middlings?
- In which way a given number of stages must be arranged in order to optimize metallurgical results and operating costs?

THIRD OPERATIONAL PRINCIPLE

"Froth flotation is a unit operation of mass concentration and the metallurgical results are merely a consequence of this fact".

The mathematical expression of this third principle is:

$$R, c = f(operation), \text{ for } t \geqslant t_m , \tag{8}$$

wherein c is the concentrate grade.

SECOND OPERATIONAL LAW - THE LAW OF CONTINUITY

In a process with multiple stages, the second law states that the global recovery is a function of the recovery of each individual stage of the main concentrated ore stream:

$$R_T = f(R_1, R_2, \ldots, R_n) \tag{9}$$

wherein R_T is the total recovery and the subscripts 1 to n refer to each individual stage.

In the same manner, the global mass concentration ratio is a function of each individual Rcm:

$$Rcm_T = f(Rcm_1, Rcm_2, \ldots, Rcm_n) \tag{10}$$

It can be demonstrated that the grade of the final concentrate, c_f, can be calculated according to the following expression:

$$cf = a \cdot R_T \cdot Rcm_T \tag{11}$$

wherein $\underline{a}$ is the grade of the feed ore.

The expressions that correlate R_T to the recovery of each stage (Equation 9) and Rcm_T to each Rcm (Equation 10) are called equation of continuity and equation of concentration respectively. Each kind of circuit has its own equations; the ones for a typical three-stage closed loop circuit are presented in Figure 6.

By applying the second law, one can analyze the effects of each intermediate stage on the final metallurgical results, rather than taking the initial and final grades of the ore into account, using the well known relation:

$$R_T = \left(\frac{a - r}{c_f - r} \right) \cdot \left(\frac{cf}{a} \right) \tag{12}$$

wherein $\underline{r}$ is the grade of the tailings.

Starting with laboratory scale experiments, the equations of continuity and concentration can be used to develop the basic flow sheet of the process, and establish the mass and metallurgical balances.
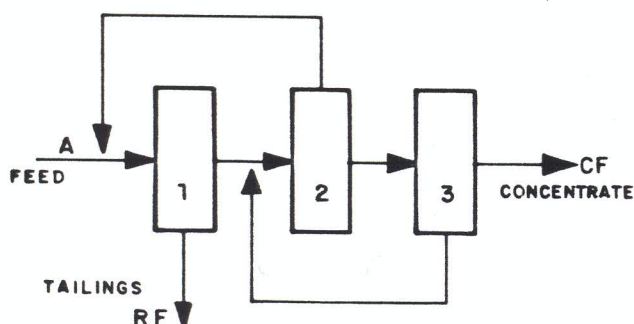
Equation of Continuity

$$R_T = \frac{R_1 R_2 R_3}{1 - R_1(1-R_2) - R_2(1-R_3)}$$

Equation of Concentration

$$Rcm_T = \frac{1 - M_1(1-M_2) - M_2(1-M_3)}{M_1 M_2 M_3}$$

Wherein $M = 1/Rcm$

Figure 6 – Three-Stage Closed Circuit

FOURTH OPERATIONAL PRINCIPLE

"In a process with more than one stage, the operational actions must aim at getting closer to the natural occurrence of the process".

The optimum arrangement of the various stages, previously optimized, leads to the "Optimized Operational Standard" (OOS), Figure 7. The hydrophobic potential (the driving force) supplied to the ore is fully retained when the plant is operated in OOS, avoiding useless operational actions.

THIRD OPERATIONAL LAW – THE LAW OF OPTIMIZATION

The best results, both from the metallurgical and economic standpoints are achieved by setting equal the metallurgical recoveries of the various stages of a closed loop circuit.

$$R_1 = R_2 = \ldots = R_n \qquad (13)$$

When this condition is achieved, the plant is operated in OOS (Figure 7). For a given recovery it occurs that:

- the circulating loads are minimum;
- the enrichment ratio is maximum;
- the number of stages is minimum;
- reagent consumption, as well as operating costs (regrinding, pulp pumping...) are minimized.

Using their practical experience, several plant operators have utilized this concept, by setting equal the grades of the recirculated products to that of the feed of a certain stage.
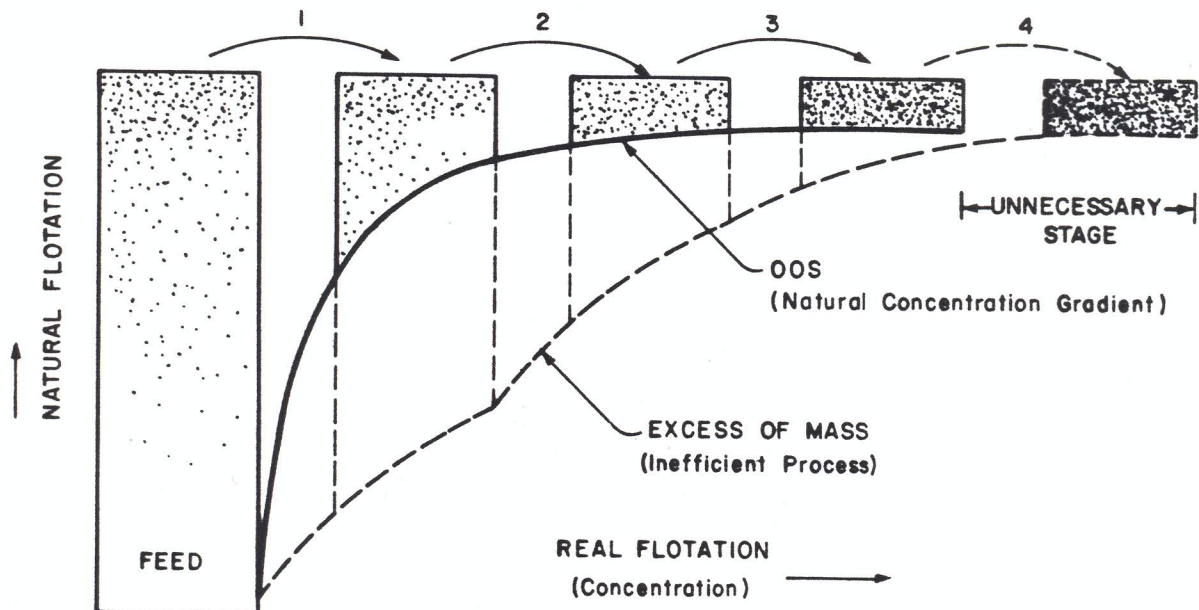

Figure 7 – Schematical   Representation of Mass Concentration
(the numbers above refer to each individual stage)

PRACTICAL APPLICATION OF THE MODEL

Two examples illustrating the application and concepts of the model are presented herein.

Example 2

This example is from a 2.5 ton/h copper sulphide pilot plant. The data refer to two types of operation: a) a typical run, the data of which were collected over a 48-hour period under typical operating conditions (reagent dosage, circulating loads, etc.), and b) a 24-hour period, in which the model concepts were applied. The use of the Operational Model assures better metallurgical results and, consequently, substantial savings since the data of the two runs can be extrapolated to the future full-scale plant operation, as indicated in Table III.

Table III – Data from a Copper Sulphide Pilot Plant. Comparison between Typical Operation and According to the Operational Model

	Typical Run	Operational Model
Recovery, %	85.6	85.4
Grade, % Cu	37.6	39.0
Cell Volume Utilized, $m^3/(ton/h)$	3.25	1.86
Circulating Loads[a] ,%	384	120
Reagent Consumption, g/ton	260	145
Operational Cost Reduction[b] ,%	–	40
Projected Annual Savings[c], US$ million	–	4.6

[a] – Sum of the circulating loads of the various stages, with respect to the feed of the plant
[b] – Calculated over the costs of the flotation and regrinding units
[c] – Taking the project criterion of the future full-scale plant into account

Example 3

The flotation flow sheet and data shown in Figure 8 have been adapted from a phosphate plant. The usual evaluation of the plant recovery is calculated according to the formula:

$$\text{Total recovery} = R_T = \left(\frac{9.95 - 2.76}{35.99 - 2.76}\right) \cdot \left(\frac{35.99}{9.95}\right) \times 100 = 78.3\%$$

According to the Second Operational Law:

$$R_T = \frac{R_R \cdot R_1 \cdot R_2}{1 - R_R(1 - R_1) - R_1(1 - R_2)} \times 100 = 78.3\%$$

wherein R_R, R_1 and R_2 are the recoveries of each individual stage indicated in the flow sheet. Obviously these recoveries are markedly different one from

the other. In addition, the hydrophobic potential supplied to the ore is unnecessarily higher in the rougher stage, causing a marked imbalancement of the plant evidenced by the high circulating loads. Applying the Third Operational Law, one concludes that by setting each stage recovery close to approximately 82%, the same total recovery of about 78% could be achieved, with the benefits pointed out earlier herein.
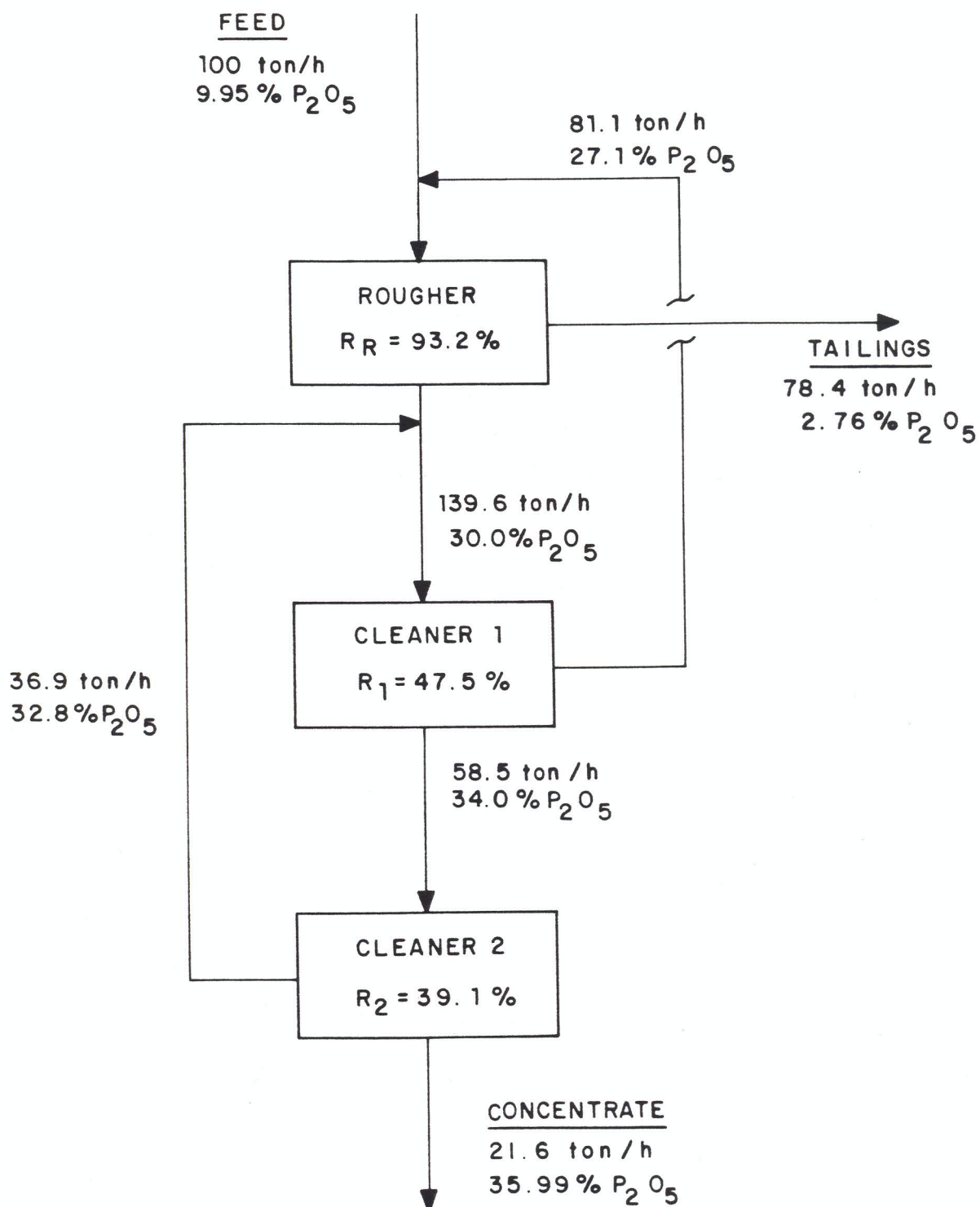
FEED

100 ton/h
9.95 % P_2O_5

81.1 ton/h
27.1% P_2O_5

ROUGHER

R_R = 93.2 %

TAILINGS

78.4 ton/h
2.76 % P_2O_5

139.6 ton/h
30.0% P_2O_5

CLEANER 1

R_1 = 47.5 %

36.9 ton/h
32.8% P_2O_5

58.5 ton/h
34.0 % P_2O_5

CLEANER 2

R_2 = 39.1 %

CONCENTRATE

21.6 ton/h
35.99 % P_2O_5

Figure 8 – Phosphate Plant Flotation Flow Sheet

CONCLUSION

The Operational Model is an original and useful tool for the analysis of operating data, optimization, and the establishment of design parameters of new flotation plants. As mentioned before, the model provides a link between the natural phenomenon (migration of particles) and the real, industrial phenomenon (mass concentration).

Examples in which the validity and practical concepts of the model have been successfully tested are listed below:
- laboratory research: the First Operational Law was corroborated in the case of iron ore (12,13) and copper sulphide (14) flotation;
- process evaluation: the performance of flotation columns was thoroughly analyzed (15);
- process rationalization: it is possible to verify that circulating loads unnecessarily increase when the Third Operational Law ($R_1 = R_2 = \ldots = R_n$) is not complied with (14). Also, reagent consumption can be minimized (16).

In summary, the model concepts are simple and its utilization presents no difficulties for those skilled in the field. In all circumstances, the metallurgical results of a flotation plant are set up by the plant operator at his own discretion, rather than being merely a consequence of the ore treated, as has often been stated so far.

ACKNOWLEDGEMENTS

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